# TERTIARY CALCAREOUS NANNOFOSSILS FROM THE CENTRAL AND SOUTHERN NORTH SEA BASINS, AND THEIR BIOSTRATIGRAPHICAL APPLICATION.

by

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Thesis submitted for the degree of Ph.D.

at University College London.

December 1988

"Geology is a capital science to begin, as it requires nothing but a little reading, thinking and hammering."
**Charles Darwin, 1835.**

"However trivial a rotten shell may appear to some, yet these monuments of nature are more certain tokens of antiquity than coins or medals .... and though it must be granted that it is very difficult to read them or raise a chronology out of them .... yet it is not impossible."
**Robert Hooke, 1699.**

## ERRATA

Title "1988" should read "1989"

ACK "Studentship for which author..." should read "studentship which the author..."

ACK "by sponsor" should read "by the sponsor"

p.27 underline Rossel pers comm.

p.61 "all well material studied consisted of >50% DC in each well" should read "well material often consisted of a considerable proportion of DC samples"

p.63 Indicate unconformities on Fig.22

p.70 Indicate unconformities on Fig.23

p.76 Indicate unconformities on Fig.24

p.90 Indicate PT22 zone on Fig.26

p.103 Barren should be typed in bold

p.118 "Gartner (1971)" should read "Gartner (1971a)"

p.125 Edit bottom line

p.132 "Lord & Bown (1987)" should read "Murray et al. (1987)"

p.136 Capital T in The

p.142 underline pers comm.

p.147 "Hamilton (1982)" should read "Hamilton & Hojjatzadah (1982)"

p.173 "Chapter 6" should read "Chapter 4"

p.175 "Teeth projecting longitudinally..." should read "teeth projecting in line with the short axis..."

p.180 "early" should read "Early"

p.253 Toweius tovae should be underlined

p.294 "FDO of Sphenolithus furcatolithoides..." should read "LDO of Sphenolithus furcatolithoides..."

p.312 Edit "Thulean Formation Formation" to "Thulean Formation"

p.315 "Gillmore" should read "G.K. Gillmore"

Bibliography :

p.355 STRADNER, H. entry for 1973 name should be in bold

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## ACKNOWLEDGEMENTS

**N.E.R.C.** - This project was carried out under the tenure of a Natural Environmental Research Council research studentship for which author gratefully acknowledges.

**Shell U.K. Exploration and Production** - As a CASE research studentship this project was jointly administered by N.E.R.C. and by Shell U.K. Exploration and Production in London. Dr M. Wannier, Dr M.J. Brolsma and Dr L. Wakefield are acknowledged for initiating the study and managing its continuity. All well material was provided by sponsor from their store of released Shell/Esso Exploration wells.

In addition to those mentioned above the author would like to thank Mr K. Kok, Mr W. Sykkema, Ms S.E. van Heck, and Dr K. Perch-Nielsen for their assistance and discussion on the calcareous nannofossil assemblages; Mr P. Osterloff and Ms K. Milson for their endless patience and priceless skills with the computer; Glyn, Noel, Richard, Wayne, Julian and Paul at the Leake Street Laboratory for providing generous assistance and the facilities for sampling; and to Ms M. Ryan, Ms E. Reardon and Ms B. Clifford for unselfish provision of office space and for putting up with endless interruptions.

**University College London** - This study was pursued at the Postgraduate Unit of Micropalaeontology, in the Department of Geology, under the astute supervision of Dr A.R. Lord, to whom a particular vote of thanks is due for his guidance and encouragement throughout the project. I am also indebted to my colleagues, Dr P.R. Bown, Dr J.A. Burnett, Dr F.M.D. Lowry, Gavin, Ian, Jeff, and Joyce for their helpful discussion and debate on matters micropalaeontological; to Jim Davy for his unparalleled technical assistance; and to them as a group for their sociability, friendliness and good humour.

**Personal** - Many people have encouraged and inspired me towards a geological goal over the years; Mr G. Pritchard, Mr J. Watson and Mr R. Farrow as school masters; Prof. C. Curtis, Prof. C. Downie, Dr J. Soper, and Dr M. Whyte as undergraduate lecturers; and Ms M. Gallagher as the original micropalaeontologist (!); their contributions are gratefully acknowledged, but there is a particular debt of gratitude which I owe to my parents, family and friends, and in particular to Cathy, without whose selfless support, love and devotion I could not have completed this thesis.

## ABSTRACT

Material from the Tertiary of 12 released Shell/Esso exploration wells from the central and southern North Sea basins was studied (739 samples) to elucidate on the distribution and character of calcareous nannofossils in this commercially valuable area. The biostratigraphical distribution of the calcareous nannofossils is outlined, together with brief remarks on the lithology and wireline log responses in each well. Remarks on the distribution of foraminifera were supplied by G.K. Gillmore as part of a parallel study.

Comparative material from sites in southern England (London Clay Formation, North London; Thanetian, Pegwell Bay; and Palaeogene of the Isle of Wight), Alabama (Lone Star Cement Quarry, St. Stephen's), New Zealand (William's Bluff near Oamaru, and Hampden Beach), South Atlantic (DSDP 36-329-29-1, 36-329-30-2), Hatton-Rockall Basin (DSDP 12-117-2-3), and Blake Plateau off Florida was also used during the study (70 samples). These localities were selected and analysed for correlation of stratigraphical levels (e.g. Late Oligocene of the Hatton-Rockall Basin), for comparison with low latitude assemblages at certain stratigraphical levels (e.g. Late Eocene of Alabama) or for close examination and scrutiny of species of Reticulofenestra (e.g. Hampden Beach, New Zealand).

A brief overview of previous work in this area, the geological history of the North Sea Basin, and the development of oil exploration is given together with sampling strategies and procedures in the introductory chapter. A new method for examining the same specimen in both light and scanning electron microscopes is established which utilises materials and methodology routinely employed in

nannopalaeontology, thus enabling the maximum amount of information to be derived from each specimen.

Each well is discussed individually in sections relating to biostratigraphically important levels. The lithology, wireline log responses, and foraminiferal data (where available) are used to supplement and complement the calcareous nannofossil data and to build up an outline stratigraphy for each well (see Figs.22-31).

The result of the biostratigraphical study is the proposal of a biozonation scheme for the central and southern North Sea Basins (NS zones 1-23, largely based on the FDO of species) which covers more of the Tertiary, in finer detail, than any of the previously published schemes, and a tentatively proposed joint calcareous nannofossil/foraminifera biozonation scheme. The NS (abbreviation for North Sea) biozonation scheme is compared with the established schemes for north-west Europe and with those of supposed wider applicability. Using the scheme as a tool of correlation the extensive formations of the North Sea Basin are compared and contrasted with the restricted and often facies variable outcrops of north-west Europe.

The taxonomic section is reduced in the interests of brevity, as the majority of the species encountered are established in the literature, however, a detailed examination of the Family Noelaerhabdaceae, in particular the genus Reticulofenestra, was undertaken and comment made on the taxonomy, structure and evolution of the group. The definition of this genus is emended and a comprehensive compendium of species produced to facilitate cross-referencing of forms.

# INTRODUCTION

AIMS OF STUDY

REVIEW OF PREVIOUS WORK

GEOLOGICAL HISTORY OF THE NORTH SEA

LITHOSTRATIGRAPHY

SAMPLING AND PREPARATION

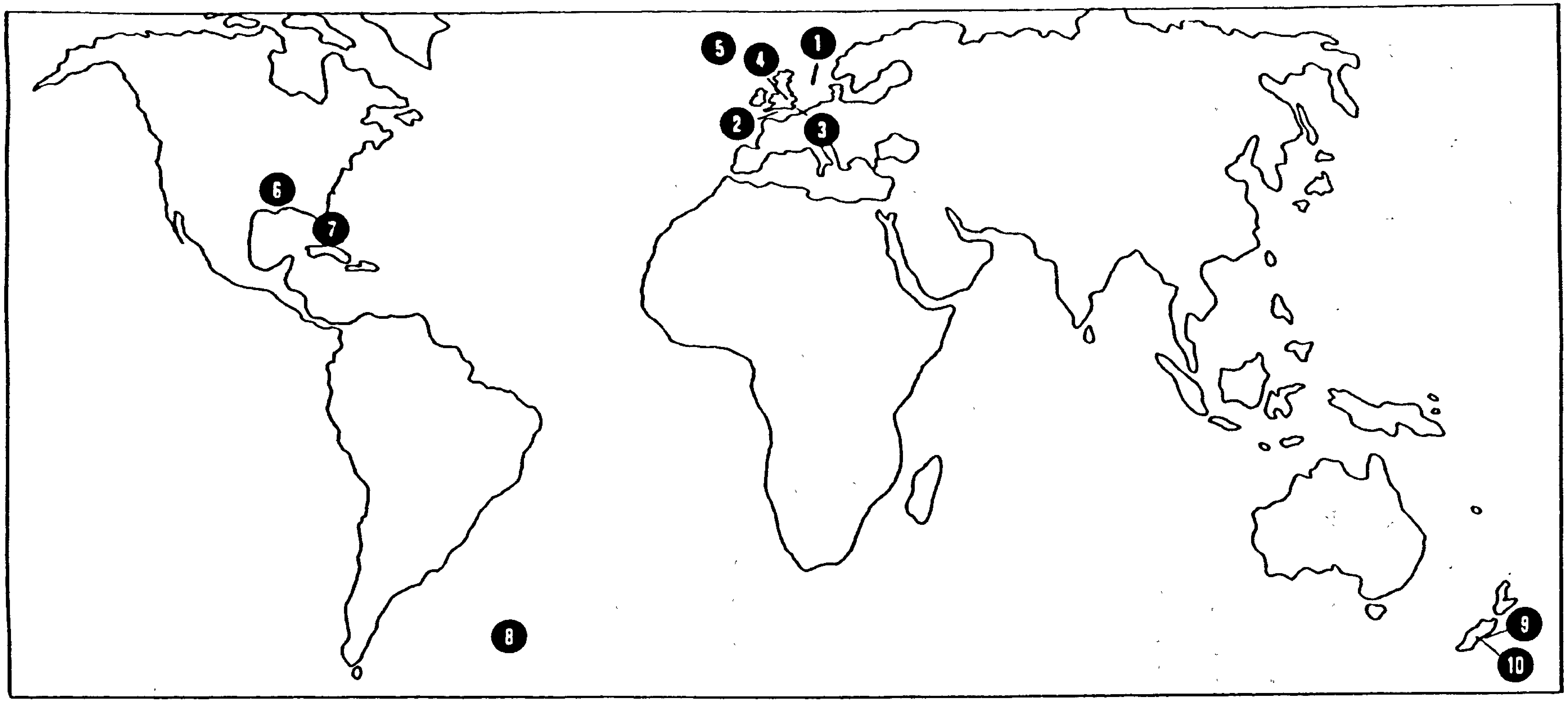
## 1.1 AIMS OF STUDY :

Biostratigraphical correlation within the Tertiary between the central and southern North Sea Basins, and with onshore sites in southern England and north-west Europe is poorly understood. The study of the biostratigraphical distribution of calcareous nannofossils via side wall samples (SWS) and ditch cuttings (DC) from released Shell/Esso exploration wells was proposed to remedy this problem. Comparative study of onshore sites was necessary to link, where applicable, the substantial offshore sequences with the 'classical', though highly facies variable, Tertiary localities of north-west Europe which have been the subject of relatively intensive study.

The physical properties peculiar to the North Sea Basin (sub-basins, grabens, inversion axes, folding, faulting, etc) and the volume of work conducted there make the erection of a local biozonation scheme most worthwhile. For the duration of this project the administrative problems of obtaining material of sufficient quality to conduct research have been overcome, and a workable biozonation based on calcareous nannofossils (to be integrated with a parallel study of foraminifera by G.K. Gillmore) is envisaged.

## 1.2 PREVIOUS WORK :

The amount of published work concerning Tertiary calcareous nannofossils from onshore sites in north-west Europe is quite considerable (see Aubry, 1986, pp.268-269). Most recent publications have involved the correlation of assemblages with magnetostratigraphy (e.g. Aubry, 1985a; Aubry *et al.*, 1986) and stratotype sections (e.g. Steurbaut and Nolf, 1986; Siesser *et al.*, 1987; Steurbaut,



1 = North Sea Basin    2 = Isle of Wight    3 = Pegwell Bay, Kent

4 = North London    5 = Rockall Basin    6 = Alabama

7 = JOIDES Hole 5, Blake Plateau    8 = DSDP Site 329, South Atlantic

9 = Hampden Beach, New Zealand    10 = William's Bluff, Oamaru, New Zealand

FIG. 1.

GEOGRAPHICAL DISTRIBUTION OF SAMPLE LOCALITIES

1988), with some refinement of the 'standard' biozonation scheme of Martini (1971) for localised areas (e.g. Belgian Basin : Steurbaut, 1988).

The amount of published work dealing with offshore north-west European Tertiary sediment is very much less in comparison, and information relating specifically to the North Sea Basin, particularly the Neogene, is almost nil. Other microfossil groups have been used to zone the North Sea Basin Tertiary, in particular foraminifera (see King, 1983, p.3-4). The work on calcareous nannofossils done in the North Sea Basin by oil companies and their ancillary service companies is clearly considerable, however, the number of studies which have actually been published is a small fraction of the total, and of these the number concerned with Tertiary assemblages is very few.

The paucity of available information is due to two main reasons. Firstly, the North Sea Basin is extensively worked by oil companies (to the virtual exclusion of outside institutions) and any information resulting from their investigations is usually kept "in house". Secondly, until recently, the strategy of drilling in the North Sea Basin was to aim for Mesozoic objectives (usually Jurassic reservoir sands) as quickly as possible. In the process the Tertiary 'overburden' was all but ignored. In the past few years, however, this policy has gradually changed, and there is now an increased awareness of the value of Tertiary reservoirs (Ekofisk, Frigg, etc.), partly in response to the decline of the Mesozoic plays. The effect of this increased and more careful sampling of the Tertiary on the biostratigraphical framework is not yet apparent because material is still generally subject to the confidentiality rules of the licence holders, and will not be widely available for several years.

In 1973 Martini and Müller looked at assemblages of calcareous nannofossils from the Neogene of the German sector of the North Sea Basin and correlated them to the 'standard' zonation scheme of Martini (1971), noting particularly the differences that were apparent in the Early Miocene. Only recently, however, have attempts been made to refine the 'standard' biozonation of Martini (1971) with specific reference to the North Sea Basin (e.g. Perch-Nielsen, 1979; Van Heck and Prins, 1987; Kok, unpub.; Varol, pers. comm.).

The experience of Van Heck and Prins (1987) was that the existing biozonation schemes were not adequate for the Danian of the central North Sea Basin. Incorporating ideas from the scheme of Perch-Nielsen (1979) they used quantitative analysis, new appearances, and evolutionary lineages to sub-divide the Early Palaeocene into 13 zones and sub-zones, whereas Martini (1971) had only recognised 4, and Romein (1979) 5 zones. See Fig.2.

Kok (unpub.) extended the investigation of calcareous nannofossils in the North Sea Basin into the Eocene and Oligocene. He compiled a range chart and compared it to published information and from this a skeletal biozonation was erected and compared to chronostratigraphy and other zonal schemes (see Fig.2.). In many ways the present study is an extension of that done by Kok (unpub.), within Shell U.K. Exploration and Production, and extends the work further to include the whole of the Tertiary.

### 1.3 GEOLOGICAL HISTORY OF THE NORTH SEA BASIN :

The North Sea Basin forms part of the large Cenozoic north-west European Basin that extends from the Atlantic shelves of Norway and the Shetland Isles to the Carpathians and the Ukraine. The North Sea Basin, including both sea and hinterland, is essentially triangular in shape. It is bounded to the east by the old Pre-Cambrian craton of the Baltic Shield, to the south by the degraded

FIG. 2.

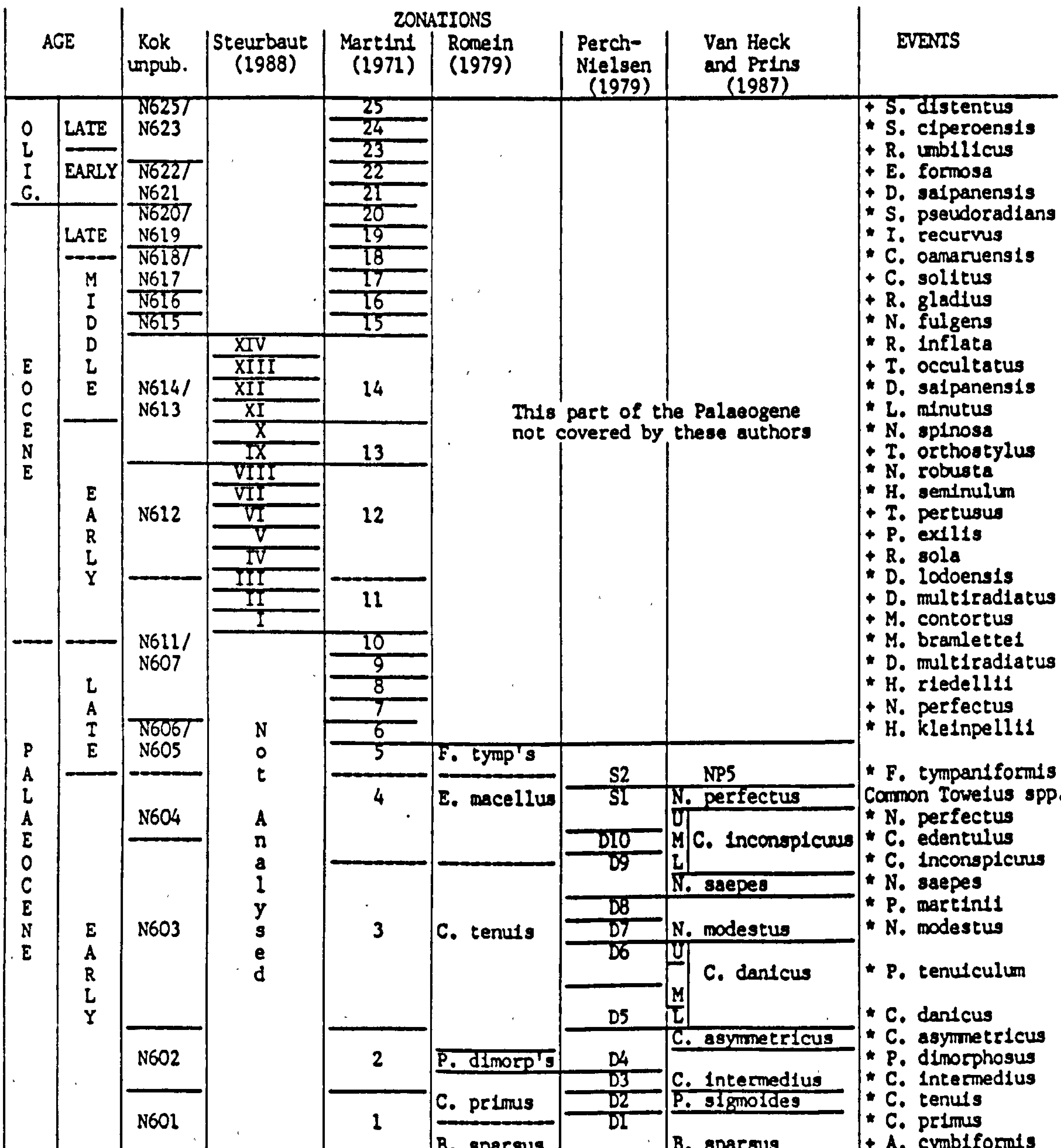


FIG. . Correlation of schemes previously applied to the North Sea Basin and North-west Europe.

* = First occurrence datum

\+ = Last occurrence datum

Hercynian fold belt, and to the north-west by the roots of the Caledonian mountain chain. See Fig.3.

It is generally agreed (Selley 1976, Ziegler, P.A. 1975, and Ziegler, W.H. 1975) that the tectonic history of the North Sea area can be divided into five major stages:

| | |
|---|---|
| i. Caledonian geosynclinal stage (Cambrian-Silurian)<br>ii. Variscan geosynclinal stage (Devonian-Carboniferous) | Intermittently tensional and compressive |
| iii. Permo-Triassic intracratonic stage<br>iv. Taphrogenic, rifting stage (Jurassic-Cretaceous)<br>v. Post rifting, intracratonic stage (Tertiary). | Dominantly tensional |

1.3.1 **Caledonian geosynclinal stage** (see Fig.4a.)- During early Palaeozoic times an elongated deep-water sea stretched from northern Norway, along the east coast of Greenland, through Scotland and continued into what are now the Appalachian mountains of North America. This seaway was a site of rapid and continuous sedimentation (Selley, 1976). Sporadic phases of compression throughout the early Palaeozoic culminated in the late Silurian Caledonian orogeny. The sediments along the axis of the geosyncline were tightly folded, faulted and locally overthrust. In Devonian times, fault-bounded basins formed within and adjacent to the Caledonian mountain chain. In these were deposited the Old Red Sandstone (see Fig.4b.).

1.3.2 **Variscan geosynclinal stage** - Simultaneously a new seaway developed, the Variscan geosyncline, which extended west to east through southern

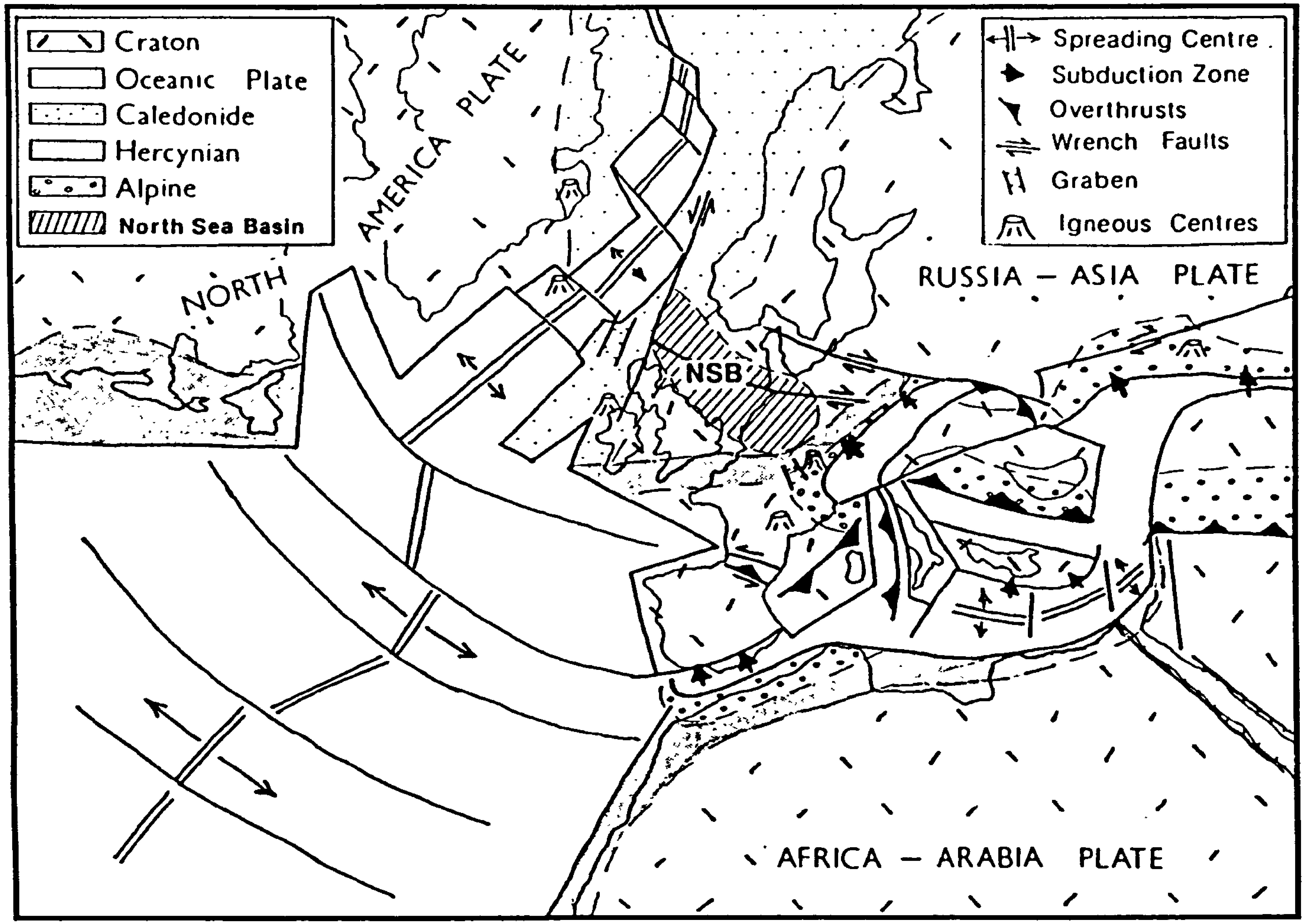



FIG. 3.

Palaeogene palaeo-tectonic framework of north-west Europe. (After Ziegler, W.H., 1975).

KEY TO FIGURE 4 :

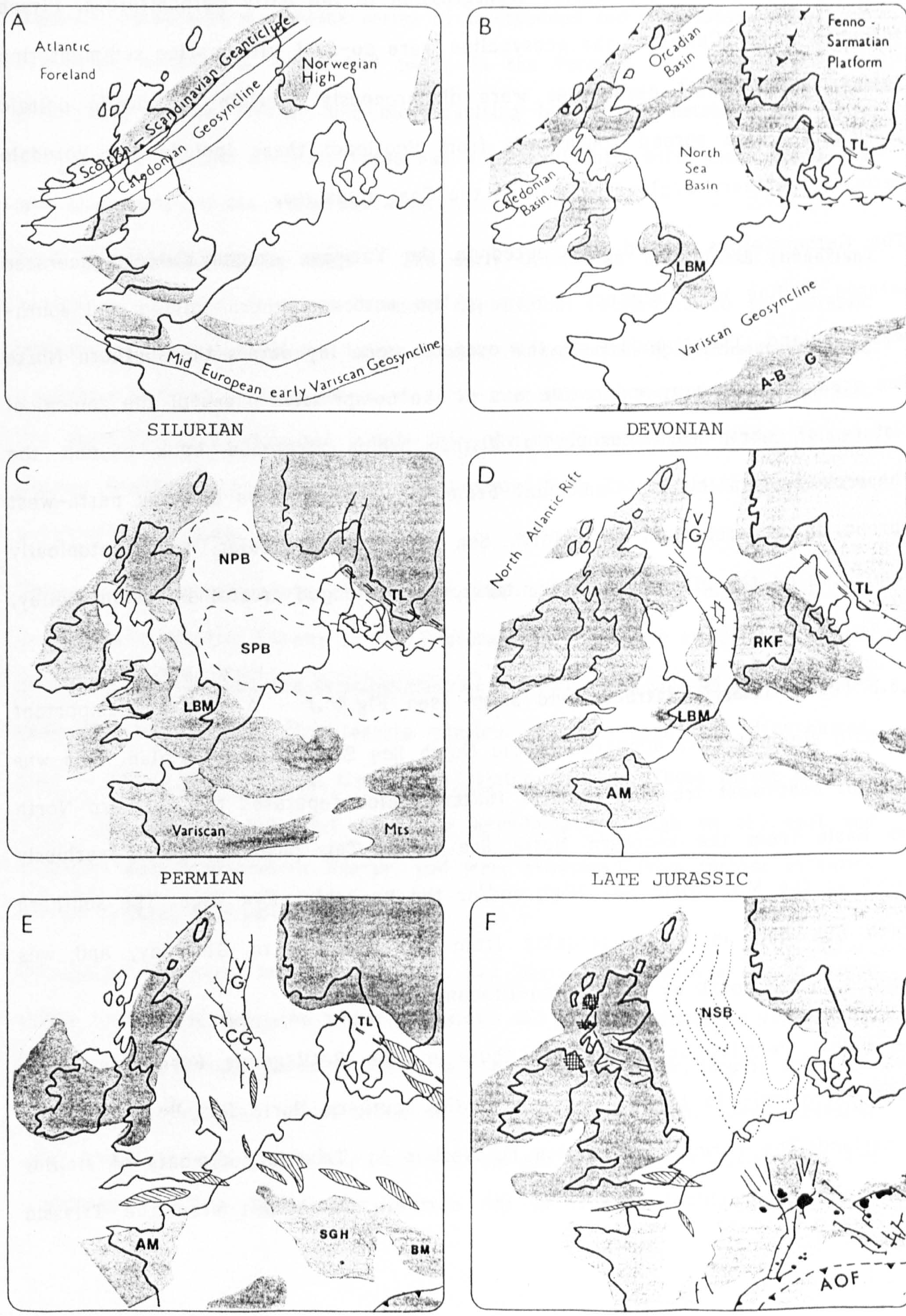
= Positive areas = Major Faults = Major Thrusts

= Inversion Axes = Igneous Province

= Basin Margins

| | |
|---|---|
| TL = Tornquist Line | A-B G = Alemanic-Bohemian Geanticline |
| NPB = North Permian Basin | SPB = South Permian Basin |
| LBM = London Brabant Massif | AM = Armorican Massif |
| VG = Viking Graben | RKF = Ringkobing Fyn High |
| CG = Central Graben | SGH = South German High |
| BM = Bohemian Massif | NSB = North Sea Basin |
| AOF = Alpine Orogenic Front | |

FIG. 4.




SILURIAN

DEVONIAN

PERMIAN

LATE JURASSIC

LATE CRETACEOUS

PALAEOCENE

Ireland, south-west England and across southern Germany. The Variscan foreland was covered by a major marine transgression in the early Carboniferous. Flysch turbidite sands (Culm) of the geosyncline were co-eval with marine sedimentation further north. Shelf carbonates were diachronously overlain by paralic deltaic sediments which spread southwards from Scotland; these include the Yoredale Series of northern England as well as the Coal Measures.

The Carboniferous period culminated in the Variscan orogeny which generated intense folding and incipient metamorphism across southern Ireland and south-west England. The boundary of the orogenic zone lay across the southern North Sea area. This orogeny marks the end of the compressive phase of the geological history of north-west Europe, a history which stretched back beyond the Phanerozoic into the Pre-Cambrian. From the Carboniferous onwards north-west Europe in general, and the North Sea Basin in particular, was tectonically dominated by the effects of intermittent, but prolonged crustal extension (Selley, 1976).

1.3.3 **Permo-Triassic intracratonic stage** (see Fig.4c.) - A new and important tectonic element first appeared in the North Sea Basin in the Permian. This was a major east-west trending positive feature which separated the northern North Sea Basin from the southern North Sea Basin. This positive axis is variously known as the Mid North Sea High and/or the Rynkøbing-Fyn High. The southern North Sea had an axis stretching from the Pennines to Germany, and was bounded to the south by the London-Brabant Massif.

The oldest Permian sediments are those of the Rotliegende Formation which occur extensively in the sub-surface of the southern North Sea Basin and The Netherlands.The Permian succession is overlain by Triassic sediments of similar facies and geographical extent. In the northern North Sea area the Triassic sequence consists of a complex series of interbedded red sandstones, shales and evaporites. Subsidence, which had begun in the Permian in a gentle manner, accelerated in the Triassic and block-faulting led to the establishment of a system of horsts and grabens. These had a predominantly north-south trend - a new orientation for the North Sea area.

1.3.4 **Taphrogenic rifting stage** - The early Cimmerian movements (Rhaetian) marked a transition from the Triassic depositional framework to the Jurassic sedimentary regime. With the Lower Jurassic transgression epicontinental marine conditions returned to large parts of north-west Europe. Marine ingressions into the North Sea area originated mainly from the newly established North Atlantic Seaway through the northern North Sea, but also from Tethys via the Paris Basin and southern England.

The main palaeogeographic features at this time were the opening of the Arctic/North Atlantic Seaway in the Pliensbachian and, more importantly in the context of this project, the establishment of the North Sea Graben system as the dominant rift complex. This feature consists of three connected rifts named, from north to south, Viking, Central and Dutch Grabens. These divide the Mid North Sea High to the west from the Rynkøbing-Fyn High to the east and continue south into onshore Europe, and were prevented from further extension by the Variscan fold belt.

Throughout the early Jurassic the North Sea Basin lay beneath a sea in which shales were being deposited whilst persistent and gradual subsidence took place. During middle Jurassic times an extensive blanket of sandstone, largely deltaic in origin, was deposited across much of the North Sea region. Locally basaltic lavas were extruded giving rise to peripheral zones of volcaniclastic sands and bentonitic clays (e.g. Fuller's Earth).

In the northern North Sea there is evidence for continuous differential subsidence of the graben floor during the Triassic and throughout the Jurassic. In the Viking-Central Graben the late Jurassic is represented by deeper water shales that locally contain turbidite sands. Late Jurassic shales are often rich in organic matter and constitute an important oil-source rock in the North Sea Basin (see Fig.4d.).

A phase of tectonic movement occurred at the end of the Middle Jurassic and at the Jurassic/Cretaceous boundary another major rifting phase took place throughout the Viking-Central Graben (Late Cimmerian phase).

The early Cretaceous was essentially a period of transgression with marine glauconitic shoal sands (the Greensands of southern England) diachronously overstepping older formations around the basin margin. In the North Sea Graben system several minor rifting phases occurred during the Cretaceous. The Viking and Central Grabens continued to subside rapidly and received thick lower Cretaceous shales (up to 500m).

The late Cretaceous was a time of quiescence when nannofossil muds with foraminifera were deposited below the effective wave base of an extensive shelf sea (see Fig.4e.). The resultant micritic limestones and marls in the central and southern North Sea are generally indistinguishable from those which crop out onshore.

With the Laramide phase of rifting, deposition of chalk came to an end in the North Sea area. The movements resulted in submarine melanges of semi-consolidated chalk being shed off fault scarps and re-deposited in deeper parts of the basin. Inversion movements occurred whereby minor basins peripheral to the main trough were uplifted.

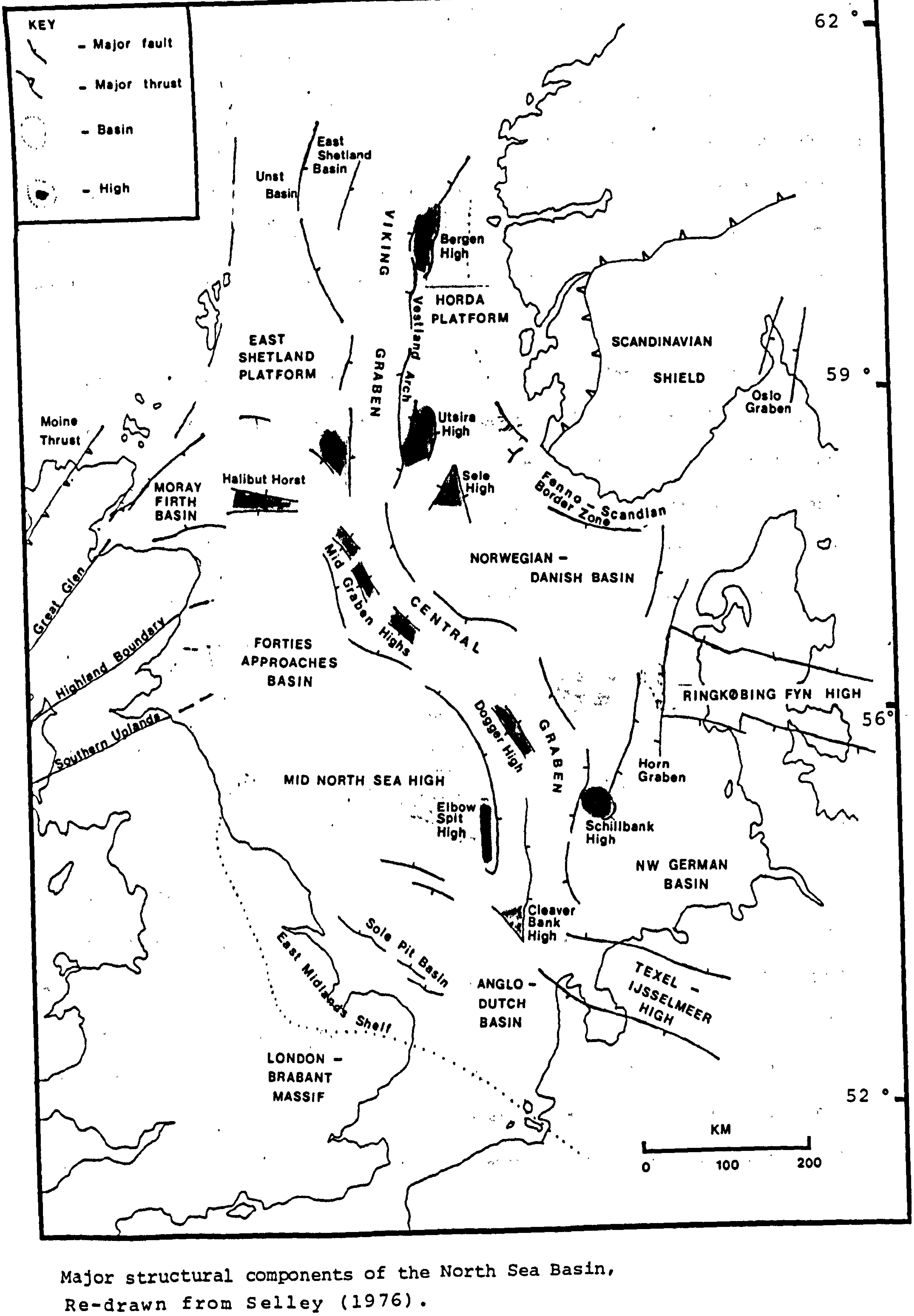
**1.3.5 Post rifting, intracratonic stage** (see Fig.4f.) - A great change took place in the palaeogeography, and therefore in the depositional pattern, of the North Sea area from the late Cretaceous to the early Tertiary; from almost total submergence to almost total emergence of a landmass in which the shape of the present day British Isles could be seen quite clearly. There is good evidence for these changes in the North Sea, in particular the influx of non-carbonate sediment from the uplifted mainland in the west, and in widespread tuffs (Lovell, 1983).

The Laramide tectonic phase marked the beginning of a new episode of subsidence of the whole North Sea Basin, which lasted until the present day. The main new element in the geological framework at this time was provided by the oceanic spreading centres that established themselves in the Palaeocene in parts of the North Atlantic rift system. These centres lay between Greenland and north-west Europe and provided the 'motor' to move the European plate complex south-eastwards towards the Alpine subduction zones in western Tethys.

During the Tertiary the North Sea Basin continued to subside and great thicknesses of sediment accumulated in it. The deep basin axis trends approximately north-south, but includes a number of 'dog-legs' which reflect the underlying graben systems (see Fig.5.).

1.3.5.1 PALAEOCENE - In Early Palaeocene times the Outer Moray Firth and northern North Sea Basins were deep-water areas in which turbidite sands were deposited. The coast from which these sands were derived appears to have been close to the present day Scottish coast and Parker (1975) presented evidence from the mapped sand distribution that the supply was from a series of widely separated point sources, perhaps canyons in the basin slope. At the same time the intra-basinal positive areas were being gradually submerged by the deepening

FIG. 5.




Major structural components of the North Sea Basin, Re-drawn from Selley (1976).

sea and marine muds were deposited over them and in distal areas (Deegan and Scull, 1977).

Stewart (1987) recognised ten depositional sequences within the early Palaeogene sediments based on seismic data. He noted that these sediments have a gross wedge-like form which dips and thins in a south-easterly direction along the Central Graben from a maximum of >1200m in the Wytch Ground Graben to <200m in the southern Central Graben (see Fig.6a.). The section also thins and rises westwards towards the coast of Scotland with a present day erosional limit within the Moray Firth Basin. The Palaeocene sediment distribution pattern has been accounted for, as described above, by interpreting the thick sequences of the north-west as proximal sediment wedges and the thin sequences of the south-east as their distal deep-water equivalents (Ziegler, W.H., 1975; Parker, 1975; Deegan and Scull, 1977). Knox et al. (1981) pointed out that this theory presupposed that the Tertiary North Sea Basin was already established in Palaeocene times and suggested that Palaeocene sedimentation was largely restricted to Mesozoic graben zones, with the remainder of the North Sea area undergoing only slight and intermittent subsidence and sedimentation.

The structural setting of Palaeocene sedimentation was broadly established in post-Danian times (Knox et al., 1981). Following the deposition of the Danian chalk and marl, the North Sea Basin was subjected to widespread uplift and erosion. Danian sediments were removed from all but the Viking Graben, Moray Firth Basin, and Central Graben areas.

This basic structural regime persisted (with local modifications) throughout Palaeocene times, with sedimentation being more or less restricted to graben-controlled basins. Later during the Palaeocene there was a change in depositional style and a major coastal-deltaic complex prograded eastwards over the Moray

## Isopach maps

Figure 6.

A = Palaeocene isopach map in tens of metres (Top of the Ekofisk Formation to the Base of the Balder Formation).

B = Balder Formation isopach map in tens of metres.

Figure 7.

A = Eocene isopach map in tens of metres.

B = Oligocene isopach map in tens of metres.

Figure 8.

A = Miocene isopach map in tens of metres.

B = Tertiary sediments isopach map in tens of metres.

Figures all adapted from Bjorslev Nielsen *et al*, 1986.

Abbreviations :

MFB = Moray Firth Basin

HH = Halibut Horst

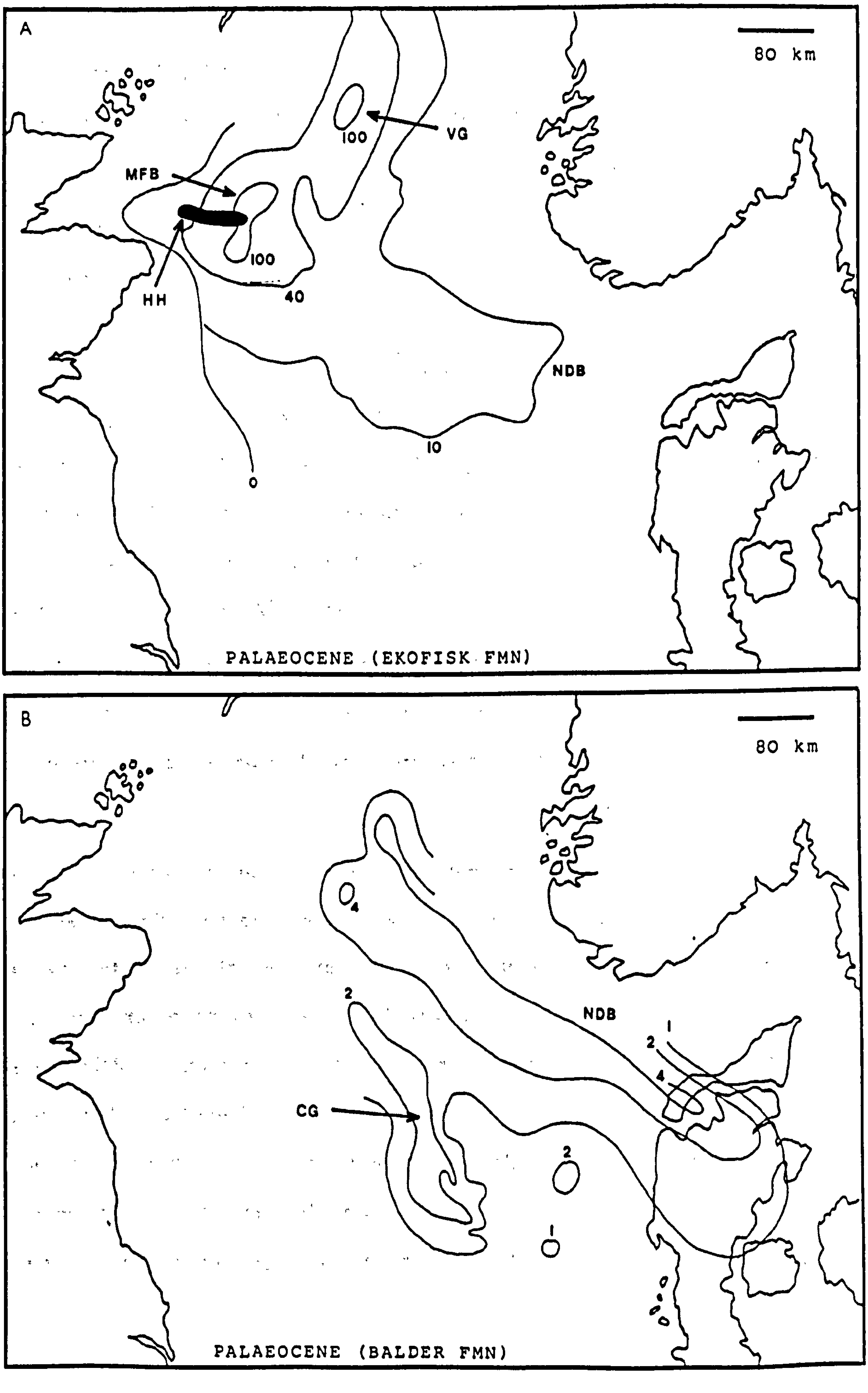
CG = Central Graben

VG = Viking Graben

NDB = North Danish Basin

Explanation of Figs. 6 - 8

FIG. 6


A
80 km
100
VG
MFB
100
HH
40
NDB
10
0
PALAEOCENE (EKOFISK FMN)
B
80 km
4
2
NDB
1
2
4
CG
2
1
PALAEOCENE (BALDER FMN)

Firth area, overlying the earlier turbidites (Parker, 1975). This complex produced a large influx of sediment into the deeper turbidite basin from across the whole width of the prograding slope.

A major two-fold post-Danian division of Palaeocene sediments (marked by pale greenish shales with a rich foraminiferal fauna in the lower part and dark, carbonaceous and possibly brackish-water shales in the upper part) suggests that sedimentation can be viewed in terms of two cycles. Each cycle commenced with widespread regression, uplift of the Orkney-Shetland Platform, and Central Graben subsidence. This was followed by a phase of widespread transgression, with uplift to the west, subsidence in the Moray Firth Basin, and volcanism (Knox et al., 1981). The two-fold vertical division of the post-chalk Palaeocene sequence has been defined by Deegan and Scull (1977), consisting of an upper unit (Moray Group) dominated by 'deltaic' sediments and a lower division (Montrose Group) dominated by submarine fan deposits. These divisions were recognised by Parker (1975), but regarded as different developments of the same basic sedimentary regime.

At the end of the Palaeocene volcanic eruptions, which had previously occurred intermittently, culminated in a series of ash-fall deposits (the Balder Formation) tens of metres thick which are preserved over most of the North Sea Basin (see Fig.6B.). This ash unit is an excellent seismic reflector and a reliable synchronous marker horizon. Evidence of volcanic centres of Palaeocene/Eocene age is widespread in the north-west British Isles (Hebridean Province), in the Faeroe-Shetland region (Thulean Province) and in the Rockall-Faeroe troughs (Malm et al., 1984). These areas, especially the Thulean Province, contain abundant basaltic rocks of the correct composition and age to match the ash units and tuffs of the North Sea Basin.

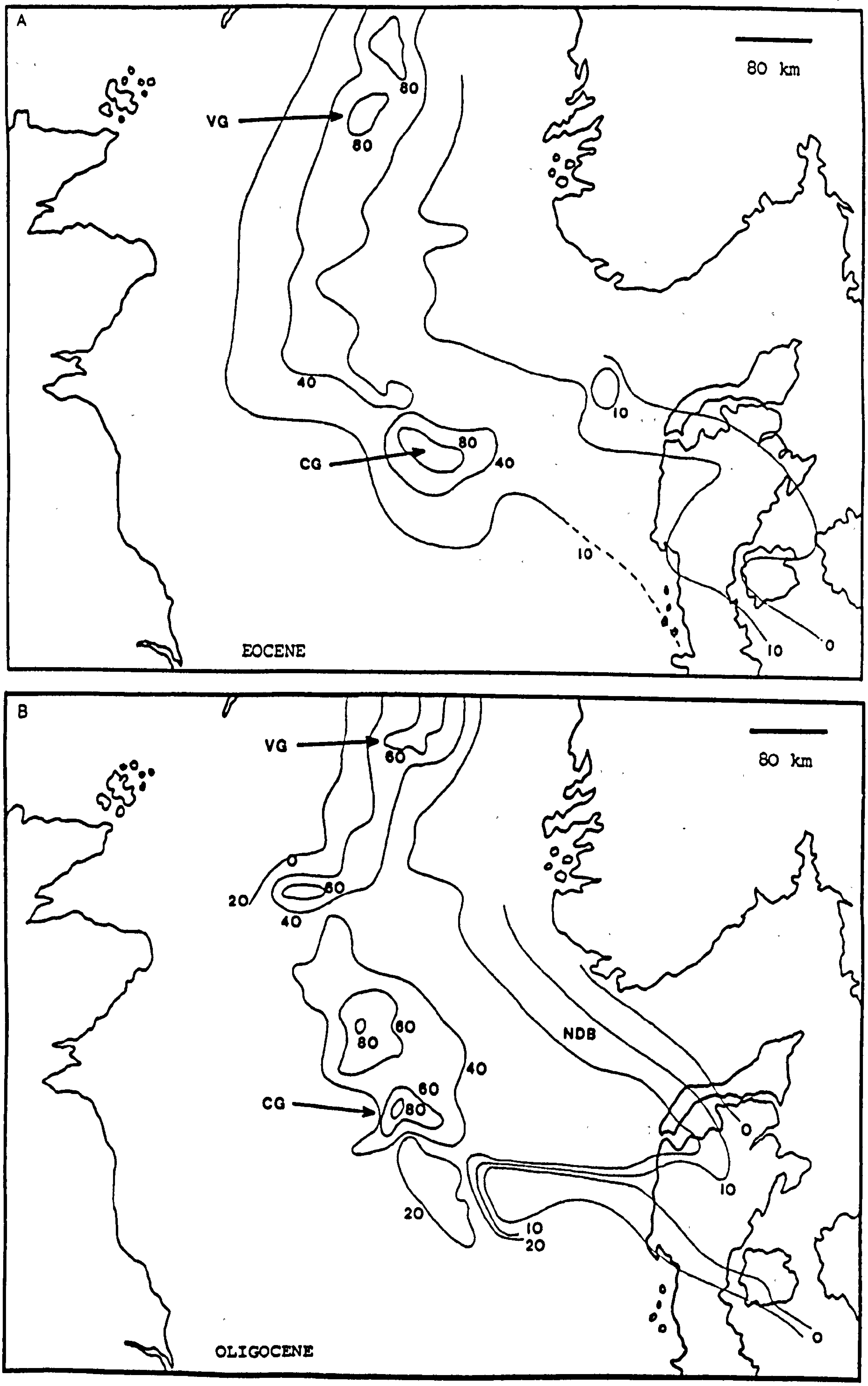
Comparison of grain size, bed thickness and abundance in North Sea wells in the northern North Sea indicated that the source volcanism for this area was located to the north and that the ashes were blown generally southwards (Malm et al., 1984). In the southern North Sea a separate Skagerrak volcanism episode along the tectonic Tornquist zone was suggested as a major source for these ashes. Multiple centres situated north to north-west of the North Sea area and in the Skaggerak can best explain the regional distribution of the tuffs and ashes.

Jacqué and Thouvenin (1975) pointed out that such volcanism must have been connected with an important tectonic event (Thulean phase), such as vertical or tangential movement on at least a North European scale. The opening of the North Atlantic (Norwegian Sea area) is known to have gone through a very dynamic phase at this time, with a maximum of activity around 55Ma.

1.3.5.2 EOCENE - Further downwarping of the basin, probably associated with the volcanism, resulted in a major transgression in the Early Eocene. Marine muds were deposited above the ash beds throughout the basin, except in the marginal areas where localised sand deposits accumulated (Deegan and Scull, 1977).

During the Eocene the clastic supply from the West Shetland Platform and the Scottish Highlands gradually diminished (Ziegler, P.A., 1981). Subsidence was greatest in the Central Graben where the deepest part is situated more than 3000m below present sea level. In the Viking Graben the base of the Eocene is only locally below 2000m. The thickness of Eocene sediment, however, is greatest in the Viking Graben, where it exceeds 800m (see Fig.7a.). Major accumulation of sediment and subsidence in the Moray Firth Basin had ceased by this time (Bjorslev Nielsen et al., 1986).

FIG. 7


A
80 km
VG
80
80
40
CG
80
40
10
10
10
0
EOCENE
B
80 km
VG
60
0
20
60
40
60
80
40
NDB
60
CG
80
20
10
20
0
10
0
OLIGOCENE

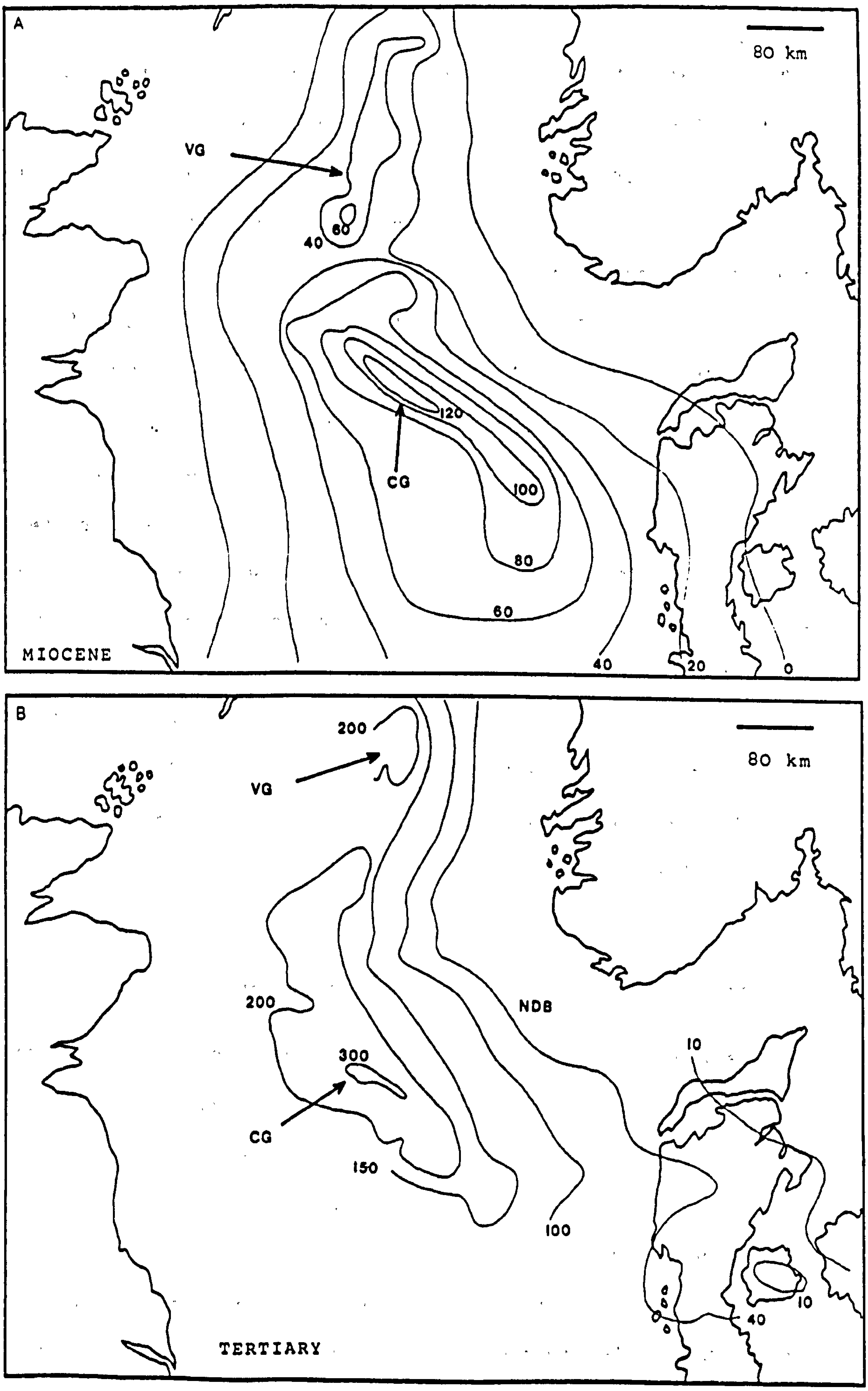
1.3.5.3 OLIGOCENE - (See Fig.7b.) The bulk of the Oligocene and younger clastic fill of the North Sea Basin was derived from eastern and south-eastern sources. In the central North Sea, relatively deep-water shales reach thicknesses of up to 1000m. Glacially induced eustatic sea level changes strongly influenced the later Oligocene and younger sedimentation patterns in the North Sea by causing regionally correlatable disconformities (Ziegler, P.A., 1981). Subsidence was greatest in the northern part of the Central Graben where the base of the Oligocene sediments are presently at depths of >2500m.

1.3.5.4 MIOCENE/PLIOCENE - The Miocene and Pliocene development of the North European river system was coupled with an acceleration of sedimentation rates in the North Sea where Neogene sediments, deposited under upward-shallowing conditions, attained thicknesses of approximately 2000m; this reflects an increase in sedimentation rate (Ziegler, P.A., 1981). The base of the Miocene occurs at depths greater than 2000m in the Central Graben. In the Viking Graben post-Oligocene subsidence rarely exceeded 1000m. The Central Graben was the main depocentre of Miocene sedimentation with a sediment thickness of >1300m (Bjorslev Nielsen et al., 1986), see Fig.8a.

## 1.4 THE HISTORY OF NORTH SEA OIL EXPLORATION :

There are few hydrocarbon provinces in the world which can compare with the North Sea for the variety of its petroleum geology. It was the discovery in Holland in 1959 of the giant Groningen gas field which initiated oil company interest in this area leading to the discovery of one of the world's major oil and gas provinces. The effective start of offshore exploration in various sections of the North Sea was determined by the enactment of petroleum legislation by those countries claiming sovereignty over the waters. The mineral rights in the

FIG. 8



A
80 km
VG
40
60
120
CG
100
80
60
40
20
0
MIOCENE
B
200
80 km
VG
200
NDB
10
300
CG
150
100
10
40
TERTIARY

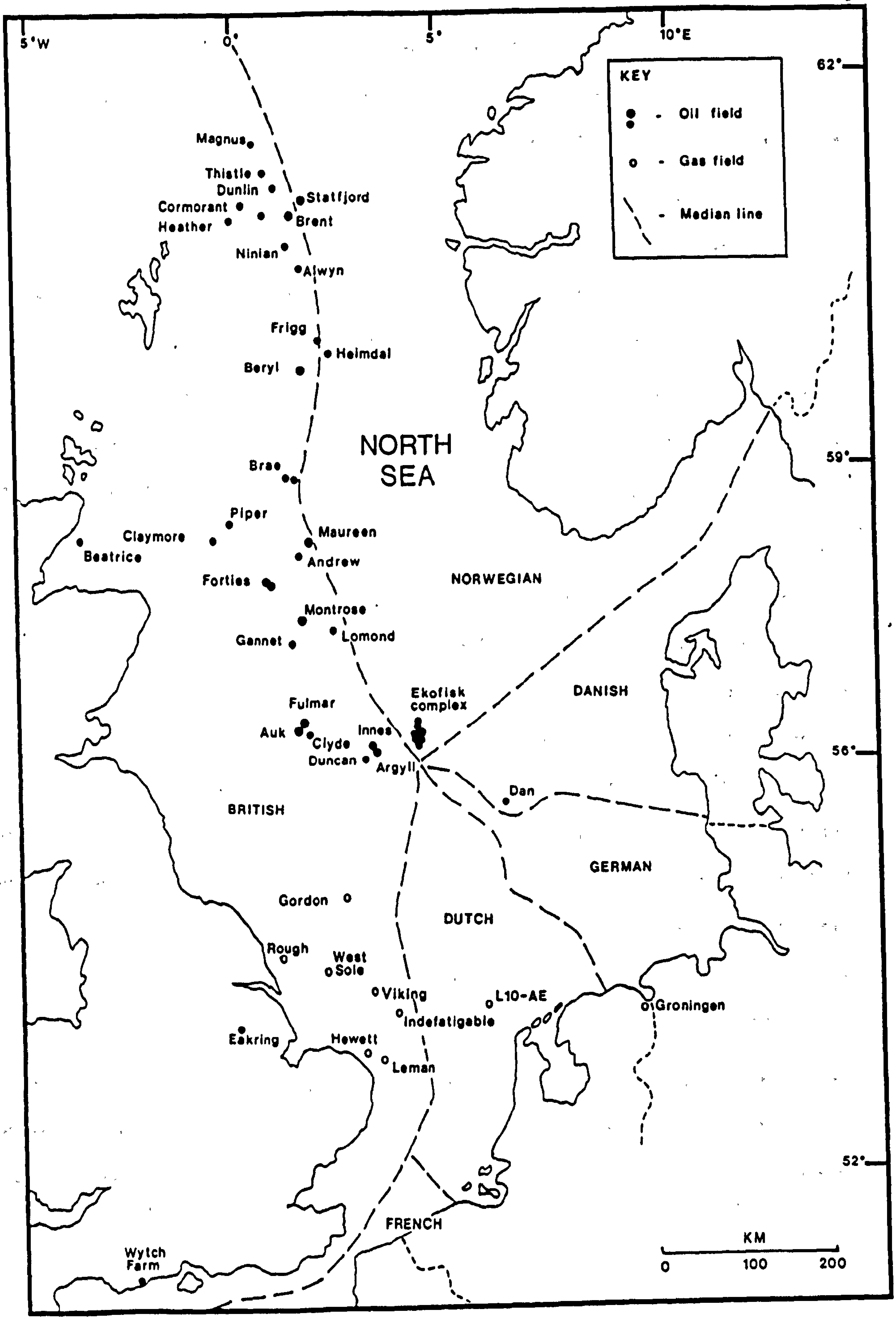
North Sea were determined by median lines. These lines, segregating the offshore limits of those countries bordering the North Sea, were established in 1964 which was the year in which the British government awarded licences for blocks of acreage in the southern North Sea. At the same time exploration went ahead in the Dutch, German and Danish sectors.

During the late 1960's gas and oil discoveries were made in all these southern sectors; however, it was not until 1970 when Phillips drilled the 2/4-1 well in southern Norwegian waters that the first major field was discovered, from the Chalk in a field now termed Ekofisk. (See Fig.9.).

In the same year B.P. drilled the discovery well of the Forties Field, which established the production potential of the Tertiary sands, and in the following June Shell/Esso discovered oil in the Jurassic sands of the Brent Field (211/29-1).

One of the most striking features of the discovery of the major offshore oil and gas deposits of North West Europe has been the rapidity with which todays position was reached considering the tentative beginnings in the mid sixties. In only twenty years or so, more than fifty named oil or gas fields have been discovered in the U.K. sector and a similar number in the Norwegian, Danish and Dutch sectors, to which must be added at least as many small hydrocarbon accumulations which could possibly achieve economic maturity at a future date. Furthermore, whilst the most widely appreciated outcome of the enterprise was the discovery of large gas and oil reserves, less appreciated has been the elucidation of the hitherto unknown geology of a very large area of the north-west European Continental Shelf.

The pace of exploration was aided by the fact that the discovery was offshore. This enabled a large coverage of relatively inexpensive seismic surveys to be obtained in the shortest possible time. Moreover the drilling that followed,




Major Oil and Gas Fields in the North Sea Basin (After Selley, 1976).

although it had to overcome severe physical and technical difficulties, was not hampered by lengthy planning applications and site preparations as would have been the case onshore. The technology of drilling and platform construction was fortunately developing at a rate which ensured that as drilling moved northwards into deeper waters the technical capacity to operate existed.

In contrast to many other hydrocarbon provinces in other parts of the world, the intervals of interest in the North Sea area have an unusually wide geological range: hydrocarbons have been proven in reservoirs ranging in age from Devonian to Tertiary. The improving seismic technology played a crucial role throughout the 1970's in clarifying what proved to be complex structural and stratigraphical geology.

Table.1. indicates the year of discovery and approximate age of reservoir of some important oil fields of the U.K. central and northern North Sea.

**1.5 LITHOSTRATIGRAPHY :**

A standard lithostratigraphical nomenclature for the Tertiary of the central and northern North Sea Basin was proposed by Deegan and Scull (1977), see Fig.10. They divided the Tertiary sequence of this area into five major groups;

v Nordland Group

iv Hordaland Group

iii Rogaland Group

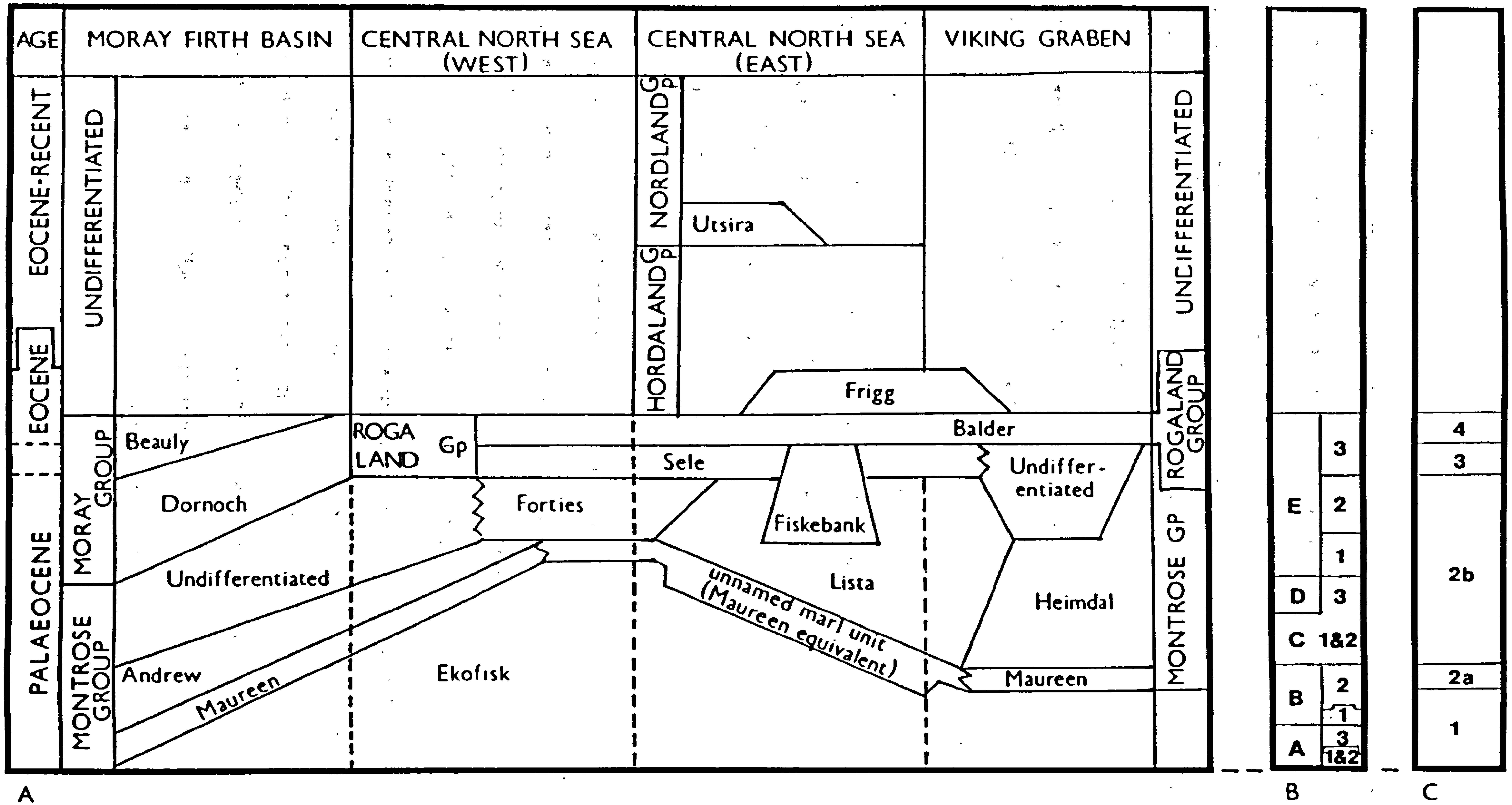
ii Moray Group

i Montrose Group

| | | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 ** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tertiary | lower | Montrose | Forties | | Frigg<br>Maureen | | Lomond | Andrew | Bressay | | | S. Montrose | | Joanie | |
| Cret. | u. | | | | | | | | | | | | | | |
| | l. | | | | | | Magnus | Fulmar | | | | | | N. Claymore | |
| Jur | u. | | | | Piper | | Tartan | Brae | Thelma | Toni | Clyde | Tiffany | | N. Brae | 16/8b-22 |
| | m. | | Josephine | Brent | Beryl | Ninian | Claymore | Tern | Beatrice | | N.W. Hutton | | Alwyn | Ettrick | |
| | l. | | | | Cormorant | | Heather | Murchison | | | | | | Duncan | |
| Tr. | | | | | Thistle | Dunlin | Bruce | Crawford | | | | | | | 211/18a-2 |
| Permian | u. | | Auk | Argyll | | Alwyn<br>Hutton | | | | | | | | | |
| | l. | | | | | | | | | | | | | | |
| C | | | | | | | | Buchan | | | | | | | |
| Dev. | | | | | | | | | | | | | | | |

** A number of new fields have been discovered up the present day.

Year of discovery and approximate age of reservoir of some important oil fields of U.K. Central and Northern North Sea Basin. (Re-drawn from Brennand, 1984). Table 1.




A = Standard lithostratigraphical nomenclature for the Cenozoic of the central and southern North Sea Basin. Re-drawn from Deegan and Scull (1977).
B = Informal stratigraphic units (Knox, Morton and Harland, 1981).
C = Informal lithostratigraphical units for the northern North Sea. Re-drawn from Mudge and Bliss (1983).

FIG. 10.

Within the Palaeocene/Eocene sediments of the Moray Firth - Forties area the recognition of a two-fold sub-division into a lower sedimentary fan sequence (Montrose Group) and an upper shelf/deltaic sequence (Moray Group) forms the basis of the lithostratigraphical nomenclature in this, western part of the central North Sea. To the east and north-east these dominantly arenaceous groups pass into the more argillaceous sediments of the Rogaland Group.

The Montrose and Moray Groups, and their distal equivalent the Rogaland Group, include all sediments deposited between the top of the Chalk Group and the top of the ash marker (Balder Formation).

The base of the Rogaland/Montrose sequence is taken at the abrupt lithological change from the calcareous deposits of the Cretaceous Chalk Group to the overlying clastic deposits, often containing reworked fragments of chalk or marl. This basal unit of reworking is called the Maureen Formation. The basal marls of this unit were deposited from distal fan/turbidite systems which provided extrabasinal fine siliciclastics mixed with submarine reworked fine calcareous material of Danian and Late Cretaceous age. During the Early Palaeocene, thick massive-bedded calcareous conglomerates developed from local gravitational processes, whereby semi-consolidated Danian and/or Maastrichtian chalk slumped off newly formed scarp slopes, scouring the marl veneer beneath.

Overlying the Maureen Formation is a sequence of overlapping sand fans which have coalesced into a sand 'sheet'; the Andrew Formation. An upper arenaceous unit, probably deposited in a submarine fan environment, is distinguished as the Forties Formation (Deegan and Scull, 1977). Silt/clay interbeds within this unit were probably derived from low concentration turbidity currents or the 'tail' part of high concentration turbidity currents (Rossel, pers. com.).

The Moray Group consists of deltaic units deposited in shallow marine and nearshore environments. Two formations are defined in the group; the Dornoch Formation and the Beauly Formation.

The Rogaland Group is more extensive than either the Montrose or Moray Groups. Three widespread and one overall restricted formations are recognised within it. At the base is an unnamed marl unit which is the time equivalent of, and interdigitates with the sand units of the Montrose Group; this is called the Lista Formation. The clays within this formation were derived from low density turbidity currents, mud flows and suspension fall out. Above the Lista Formation are two relatively thin units which have a basin-wide distribution; these are the Sele and Balder Formations. The Sele Formation consists primarily of tuffaceous shales and distal turbidite deposits indicative of a deep basinal anoxic environment, while the Balder Formation contains a higher proportion of volcanic detritus and forms a distinctive 'ash marker'. The uniformity of the Rogaland Group can be contrasted with the basinward wedging of the Montrose Group.

The Heimdal Formation is taken to include all the sands in the Viking Graben equivalent to those of the Montrose Group in the Central Graben and Moray Firth.

The rest of the Tertiary sequence above the Moray and Rogaland Groups, include the Hordaland and Nordland Groups. The Hordaland Group consists mainly of marine shales with some thin limestone streaks and localised sand units, while the Nordland Group contains predominantly marine shales and clays. The uppermost sediments of this group consist of uncompacted muds and these are usually overlain by glacial deposits.

Table 2. lists each group and formation and gives their characteristics in detail.

| GROUP/ FORMATION | WELL TYPE SECTION TYPE AREA | THICKNESS | LITHOLOGY | BOUNDARY | DISTRIBUTION & AGE |
|---|---|---|---|---|---|
| NORDLAND | Norway - 2/7-1, U.K. - 14/25-1. | 1502m - thins eastwards away from basin centre. | Predominantly marine shales and clays. They are grey to grey brown, blocky, slightly micaceous, silty in part, with occasional glauconite and some traces of sand. | Upper boundary is the present sea-bed. | Throughout the whole of the North Sea Basin. Middle Miocene to Recent. |
| UTSIRA | Norway - 16/1-1 | 419.5m in the type well. | Light greenish grey, non-calcareous, marine sands and shales, with glauconite. | Base marked by the downward transition into brown shales of | Only in centre of the Norwegian part of the North Sea. Middle to Late Miocene. |
| HORDALAND | Norway - 2/7-1 U.K. - 14/25-1 | 1221m in type well, thins eastwards. | Marine shales with some limestone streaks. Normally light grey to brown. | Base contact is marked by the tuffs of the Balder Formation. | Widely distributed throughout most of the North Sea Basin Eocene to Early Miocene. |
| FRIGG | Norway 25/1-1 | 279m in the type well. | Light brown, micaceous and carbonaceous sandstones. Lenses of greenish grey silty shale sometimes occur. | Base marked by the Balder Formation. Top Top taken where sands pass into shale of Hordaland Group. | Confined to central and southern Viking Graben. Eocene. |
| ROGALAND | Norway 2/7-1 33/9-1 | 112m in 2/7-1 and 196.5m in 33/9-1. | Argillaceous marine shales with minor sands. Shales become increasingly tuffaceous near top. | Top marked by change from tuffaceous to non-tuffaceous shales. Base marked by log break. | Widely distributed over eastern part of northern and central North Sea. Palaeocene to Early Eocene. |

Table 2.

| | | | | | |
|---|---|---|---|---|---|
| BALDER | Norway 25/11-1 | 75m in type well. | Laminated shales with sandy tuffs and occasional limestone. | Upper boundary placed where shales replaced by reddish, non-laminated sediments. | Distributed over most of North Sea. Palaeocene to Early Eocene. |
| SELE | U.K. 21/10-1 | 31m in type well. | Tuffaceous shales and silts which are grey or greenish-grey. They are finely laminated and carbonaceous. | Upper boundary defined by log characteristics and lower boundary at laminated/non-laminated sediment junction. | Widely distributed over North Sea. Palaeocene to earliest Eocene. |
| LISTA | Norway 2/7-1 | 45m in type well. | Non-tuffaceous, non-laminated shale. | Base marked by transition into marl unit. | Widespread, particularly in Norwegian sector. Palaeocene. |
| <u>MORAY</u> | U.K. 14/25-1 | 528m in type well. | Sandstones and clays of paralic and terrestial environments. | Underlain by fossil-iferous shales of Montrose Group. | Confined to Moray Firth Basin area. Palaeocene to Early Eocene. |
| BEAULY | U.K. 14/25-1 | 106m in type well. | Friable, grey poorly sorted sandstones with lignite. | Lower boundary is at base of basal lignite. | Confined to Moray Firth Basin. Early Eocene. |
| DORNOCH | U.K. 14/25-1 | 422m in type well. | Prodeltaic clays, massive sandstones and siltstones. | Top at lowest lignite bed and base as for Moray Group. | Only recognised in the Moray Firth Basin. Late Palaeocene to Early Eocene. |
| <u>MONTROSE</u> | U.K. 14/25-1 21/10-1 | 646m in 14/25-1 and 393m in 21/10-1. | Sandstone with basal re-worked limestone and marls. | Top marked by change to laminated shales of Sele Formation. Base at contact with non-clastic chalk or marl. | Well developed in Moray Firth, Viking and Central Grabens Palaeocene. |

Table 2. cont'd

| | | | | | |
|---|---|---|---|---|---|
| FORTIES | U.K. 21/10-1 | 239m in type well. | Interbedded sandstones, siltstones and clays. Become predominantly sandy higher up. | Lower boundary at sonic log response to higher velocity Andrew Formation. Upper one at Sele shale/Forties sand interface. | Extends as a wedge from the Halibut Horst to Forties area. Late Palaeocene. |
| ANDREW | U.K. 14/25-1 | 302m in type well. | Predominantly poorly sorted sandstones with occasional shale interbeds. | May overly Maureen or Ekofisk Formations. | Extends from Moray Firth area south-eastwards to the Forties area. |
| MAUREEN | U.K. 21/10-1 | 60m in type well. | Mixed lithologies - pebbles and clasts of reworked Danian and Cretaceous age in a matrix of grey shales. | Rests on the Chalk Group. Change shown in sonic, gamma and dip meter logs. | Central Graben and southern Viking Graben. Thins to W. Palaeocene. |
| (CHALK) EKOFISK | Norway 2/4-5 | 127m in type well. | White,hard, crystalline limestone. Becomes more argillaceous northwards. | Overlain by marls of Danian age. Lower contact with the Tor Formation. | Widespread in U.K. and Norwegian sectors of the North Sea. Early Palaeocene. |

Table 2. cont'd

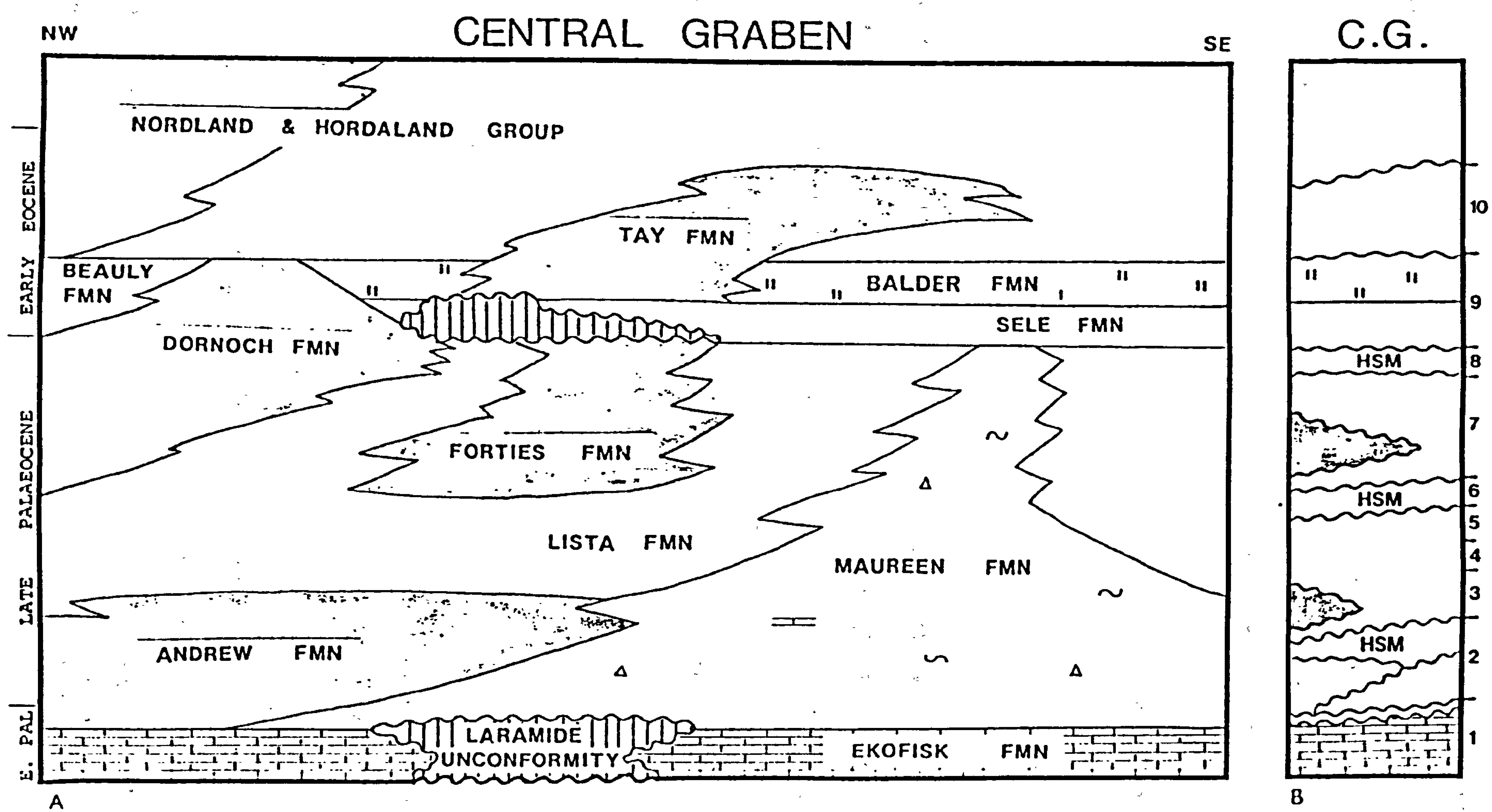
Lithostratigraphical nomenclature for the central and northern North Sea Basin. (Source - Deegan and Scull, 1977).

This framework lithostratigraphy has been used as a basis for more detailed work. e.g. Knox et al., (1981) based their five 'units' (A to E) for the Palaeocene not only on lithology and wireline logs, but also on tuff occurrence, sand mineralogy, dinoflagellate and foraminiferal distributions. Mudge and Bliss (1983) tied in their simple lithostratigraphical scheme of five informal units, based on basinwide events, with the framework of Deegan and Scull (1977). They mapped the formations further northward into the Viking Graben, where they found the broad divisions of the Montrose and Moray Groups could still be used. They also incorporated faunal and wireline log characteristics in the recognition of their units.

Bjorslev Nielsen et al. (1986) used the same lithostratigraphical nomenclature as Deegan and Scull (1977), but slightly modified it to include the observations of Knox et al. (1981) and information from the Dutch and Norwegian sectors of the North Sea. Stewart (1987) divided the early Palaeogene into ten depositional sequences using seismic data. The relationship of these, and the schemes mentioned above, to the standard lithostratigraphy of Deegan and Scull (1977) and that used by Shell U.K. Exploration and Production can be seen in Figs.10 and 11.

The lithostratigraphy of Tertiary sediments in the southern North Sea Basin is less well represented in the literature, but a summary based on Rhys (1974) and the scheme of Shell U.K. Exploration and Production (London) is given in Table 3.

The correlation of these lithostratigraphical units with the wider framework of 'standard' stages (Cavelier and Pomerol, 1986; Curry et al., 1978) for north west Europe, and the biozonation schemes of the main microfossil groups (Martini, 1971; Blow, 1969; King, 1983; Costa and Downie, 1976; Bujak et al., unpub.) is




Lithostratigraphy of the central
North Sea Basin.

A = Lithostratigraphy of the Central Graben (re-drawn from Mudge and Bliss, 1983; Stewart, 1987; and Shell Expro Exploration Reference Data Book, Fig.3.11).
B = Composite chronostratigraphic diagram for the Early Palaeogene of the Central Graben. 1 - 10 = Depositional Sequences. (After Stewart, 1987).

FIG. 11.

| * GROUP/ FORMATION | THICKNESS | LITHOLOGY | AGE |
|---|---|---|---|
| * NORTH SEA | Approximately 1650'. | Extensive clays and mud-stones. | Palaeocene to Pliocene |
| NORTH SEA SAND | 200-750' in local basins. | Grey clays, with local sands and lignite at top | Pliocene. |
| NORTH SEA CLAY | Approximately 1150'. | Clays, mud-stones and shales. Grey in colour. Patchy sands. | Early Eocene to Miocene. |
| THULEAN TUFF | Up to 100'. | Volcanic tuff, light to dark grey, brown-grey. | Early Eocene. |
| FORTIES | 200-400' on average. | Mudstones and shales. Light to dark grey. Variable sands | Palaeocene. |
| * CHALK (DANIAN) | 50-200'. | Mudstones and limestones, light grey and local chalks. | Early Palaeocene. |

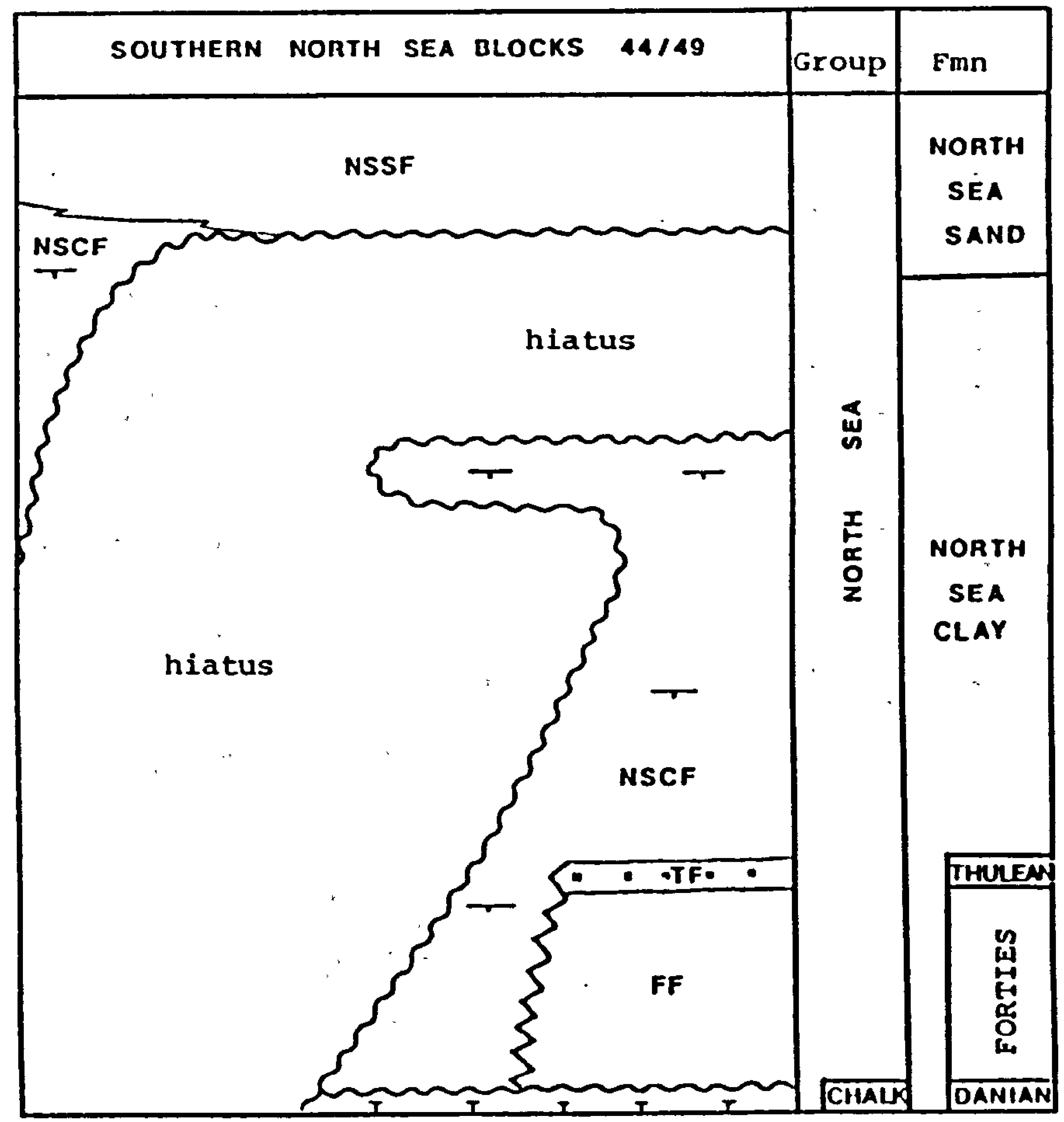



Table 3.

Cenozoic lithostratigraphy of the southern North Sea Basin. (Adapted from Rhys, 1974; and Shell Expro Exploration Note No.52).

given in Fig.12. The relationship of the calcareous nannofossil assemblages from the North Sea Basin to those of onshore sequences, and their compatibility with those quoted in the 'standard' zonation schemes, is one of the main themes of this study.

## 1.6 SAMPLE MATERIAL :

The sample material used in this study can be divided into two main categories;

i. "Well" material.

ii. "Comparative" material.

All "well" material was supplied by Shell U.K. Exploration and Production from their vast store of samples from Shell/Esso North Sea oil and gas exploration wells. The additional "comparative" material, used to elucidate specific taxonomical and/or biostratigraphical points, was kindly donated by various individuals and institutions (see below).

### 1.6.1 Provenance of North Sea well material -

Well selection - (see Fig.13.)- The selection of wells to sample was made from the list of all Shell/Esso North Sea oil and gas exploration wells which contained Tertiary strata, based on the following criteria;

i. The well had to be 'released' - only wells over 5 years old could be used as this is the time limit set for confidentiality. After 5 years (after date of abandonment) a well can be accessed by the public.

ii. As far as possible a full stratigraphic range (within the Tertiary) should be present - this was never completely possible due to the many hiatus'

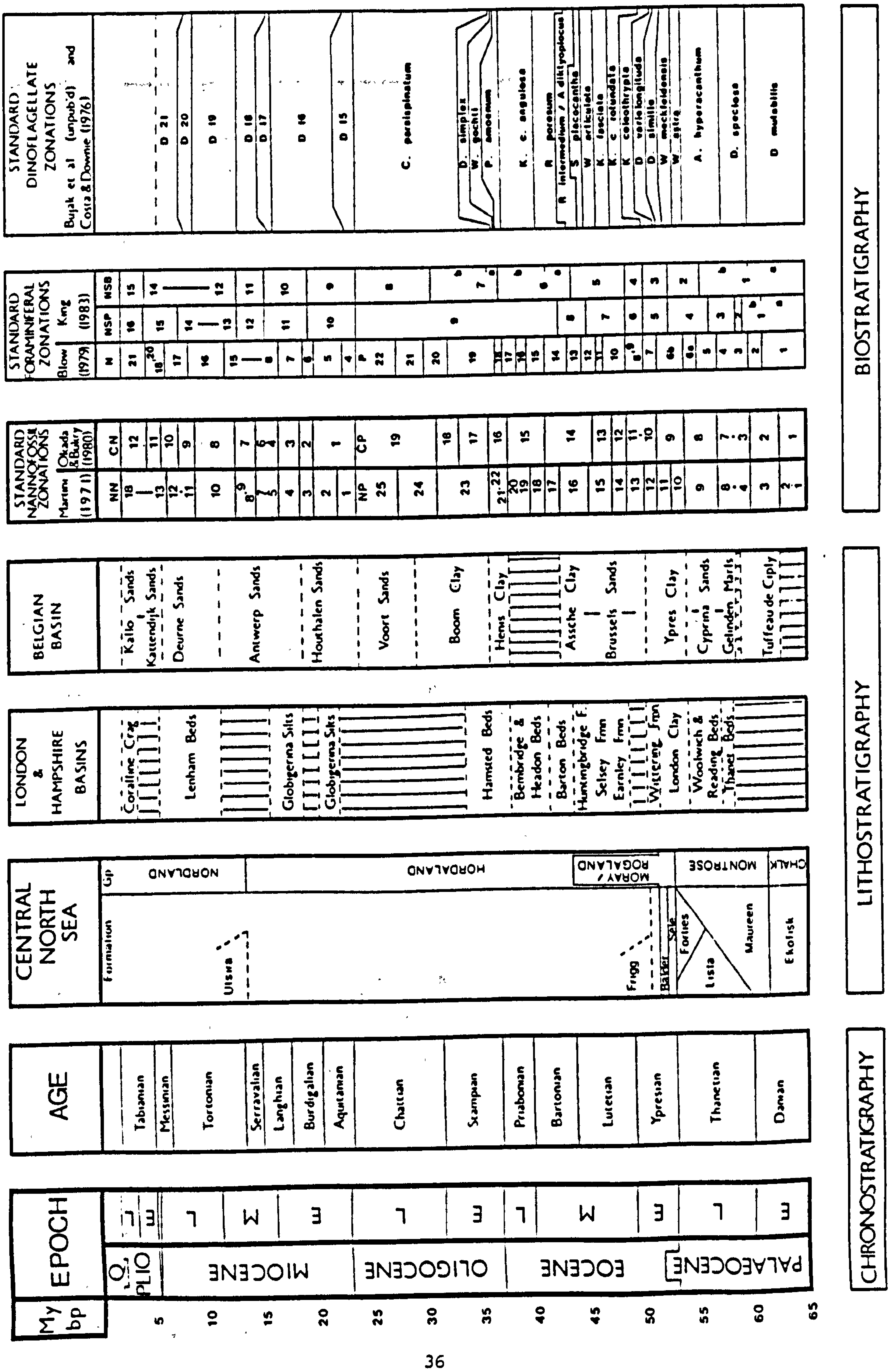

My bp
EPOCH
AGE
CENTRAL NORTH SEA
LONDON & HAMPSHIRE BASINS
BELGIAN BASIN
STANDARD NANNOFOSSIL ZONATIONS
STANDARD FORAMINIFERAL ZONATIONS
STANDARD DINOFLAGELLATE ZONATIONS
CHRONOSTRATIGRAPHY
LITHOSTRATIGRAPHY
BIOSTRATIGRAPHY
PALAEOCENE
EOCENE
OLIGOCENE
MIOCENE
PLIO
Danian
Thanetian
Ypresian
Lutetian
Bartonian
Priabonian
Stampian
Chattian
Aquitanian
Burdigalian
Langhian
Serravalian
Tortonian
Messinian
Tabianian

FIG 13.

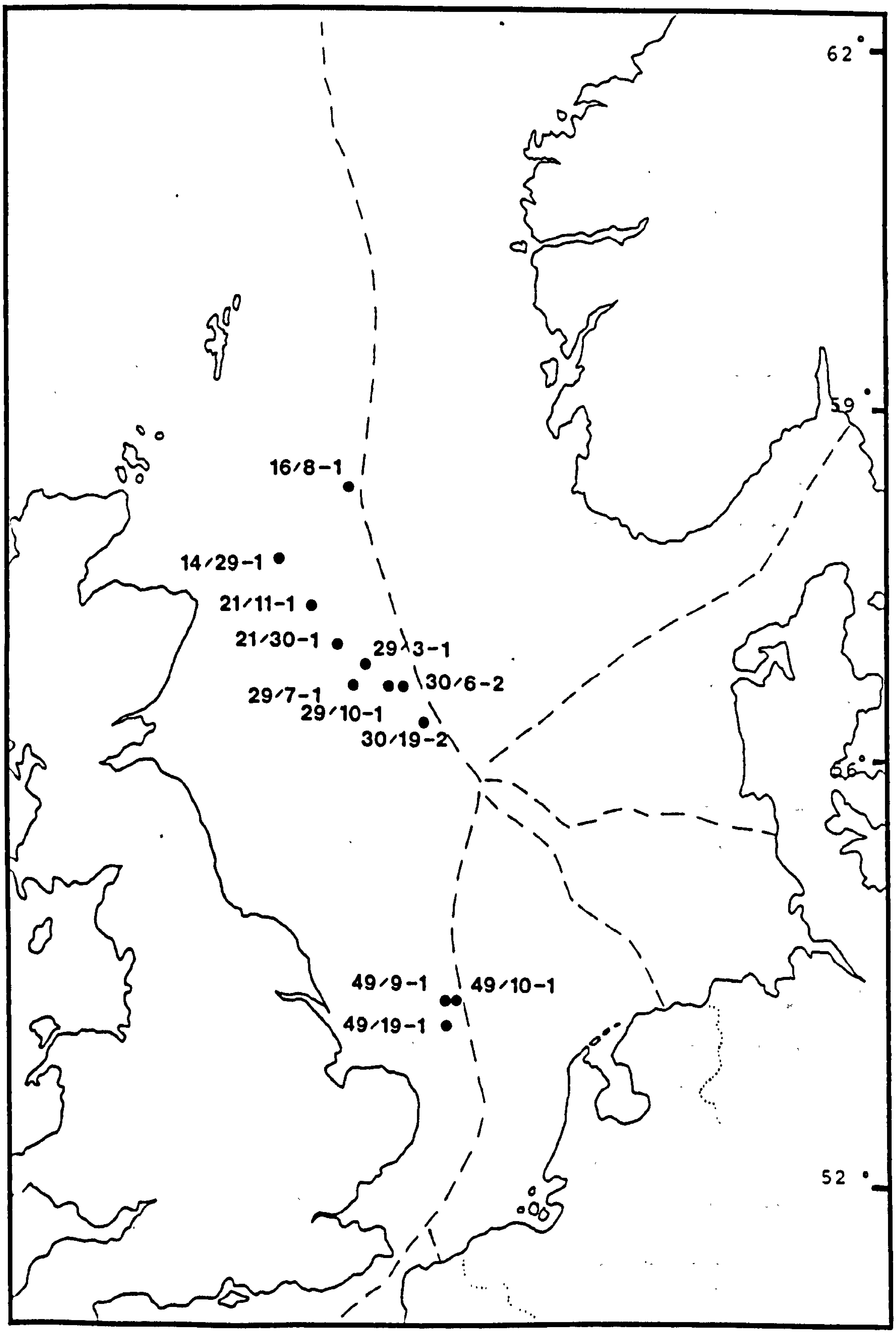



Fig.13. illustrates the position of Wells investigated in this study.

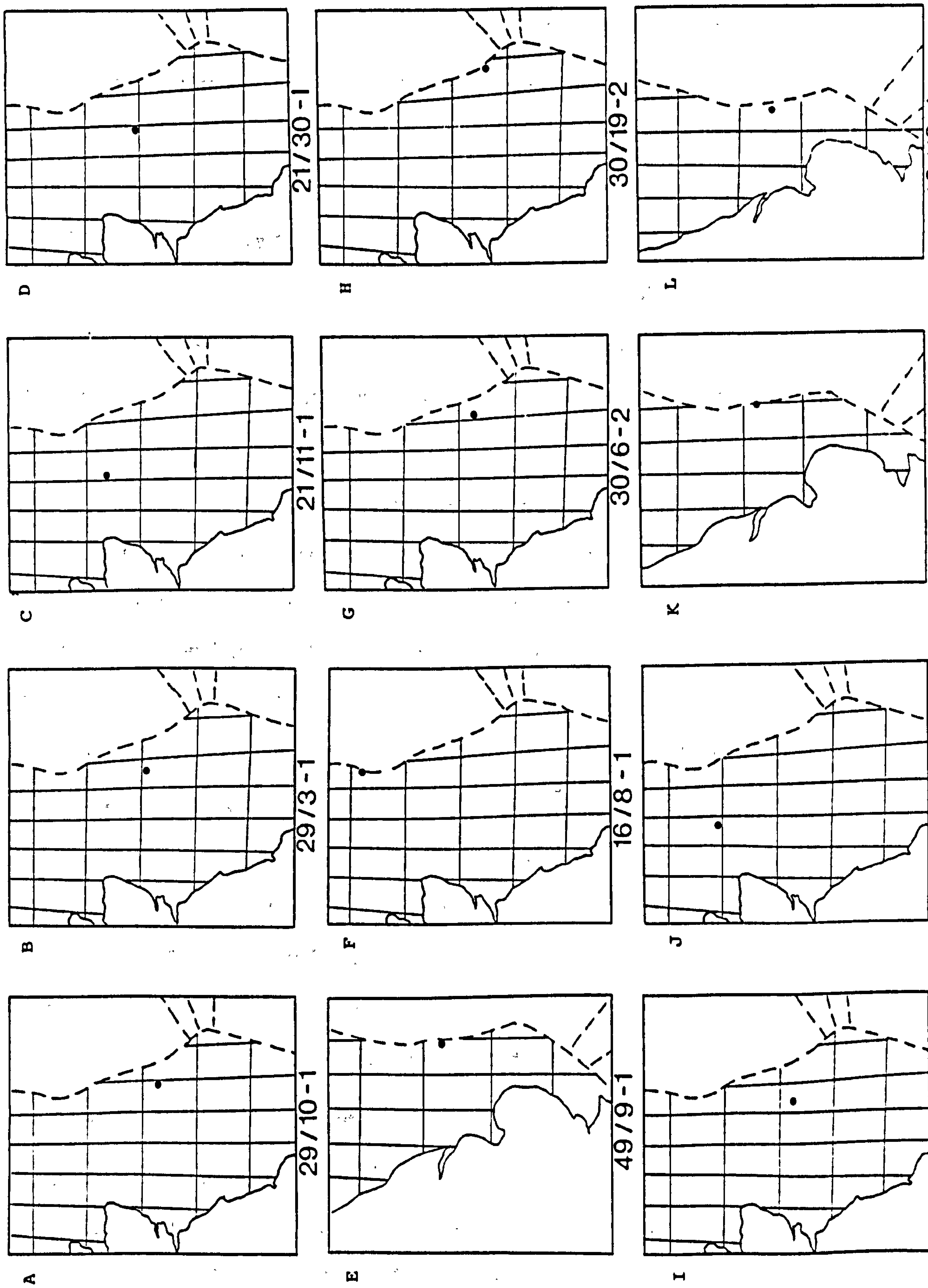
and complex sedimentary regimes present in the Tertiary sediment pile of the North Sea.

iii. A large number of side wall samples (SWS) should be present, with an even distribution throughout the Tertiary sequence - it is in the nature of exploration to cluster SWS around sand bodies (potential reservoirs) and not to take many in the Tertiary in any case. However, most wells studied did contain a reasonable number of SWS, which were supplemented by ditch cuttings samples (DC). SWS allow a desirable level of control over DC results.

iv. An even geographical spread of wells (central and southern basins) was desired and a representative selection with respect to the depth of the basin - the preceding criteria largely determined the wells chosen, but where a choice was available, the well representing a new aspect of the basin was chosen.

The first well analysed was 29/10-1 (N56°45'8.95" E01°55'7.10"; see Fig.14 .a), experience of working on this well influenced the selection of 21/11-1 (N57°38'10.00" E00°03'45.60"; see Fig.14.c), 21/30-1 (N57°05'9.60" E00°58'18.20"; see Fig.14.d), 29/3-1 (N56°50'22.195" E01°33'54.09"; see Fig.14.b), and 49/9-1 (N53°44'32.20" E02°44'23.13"; see Fig.14.e). The remaining wells studied, 16/8-1 (N58°44'53.70" E01°32'18.40"; see Fig.14.f), 14/29-1 (N58°06'26.53" E00°15'16.95"; see Fig.14.j), 29/7-1 (N56°47'10.22" E01°16'11.06"; see Fig.14.i), 30/6-2 (N56°48'35.35" E02°03'54.09"; see Fig.14.g), 30/19-2 (N56°25'42.396" E02°43'43.734"; see Fig.14.h), 49/10-1 (N53°42'57.30" E02°52'00.60"; see Fig.14.k) and 49/19-1 (N53°20'48.3" E02°45'21.80"; see Fig.14.l) were chosen to fill in certain stratigraphical levels or to extend the project into different parts of the basin. All the wells chosen had to be suitable for both calcareous nannofossil and foraminiferal research with a view to an integrated biostratigraphical study.

FIG. 14.


A
29/10-1
B
29/3-1
C
21/11-1
D
21/30-1
E
49/9-1
F
16/8-1
G
30/6-2
H
30/19-2
I
29/7-1
J
14/29-1
K
49/10-1
L
49/19-1

### 1.6.2 Provenance of comparative material -

In addition to the well material, a number of other samples were analysed to elucidate various taxonomical and stratigraphical problems. The locations of these samples are discussed below.

#### 1.6.2.1 St. Stephens Quarry (Lone Star Cement Quarry), St Stephens, Washington County, Alabama, U.S.A. -

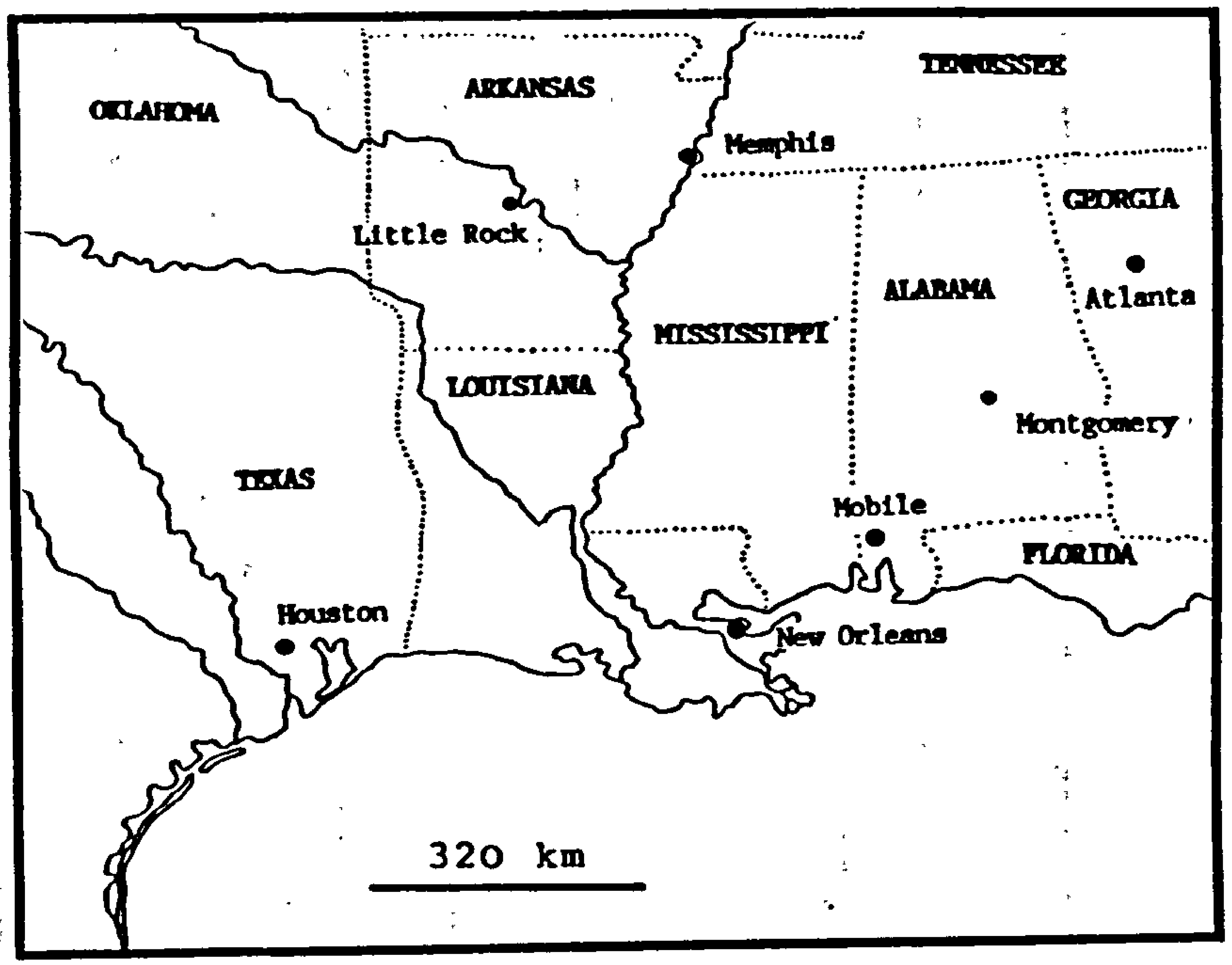
This quarry is located at St Stephens Bluff on the west bank of the Tombigbee River, 3.5 kilometres north-east of St Stephens, Washington County, Alabama, U.S.A. see Fig.15.

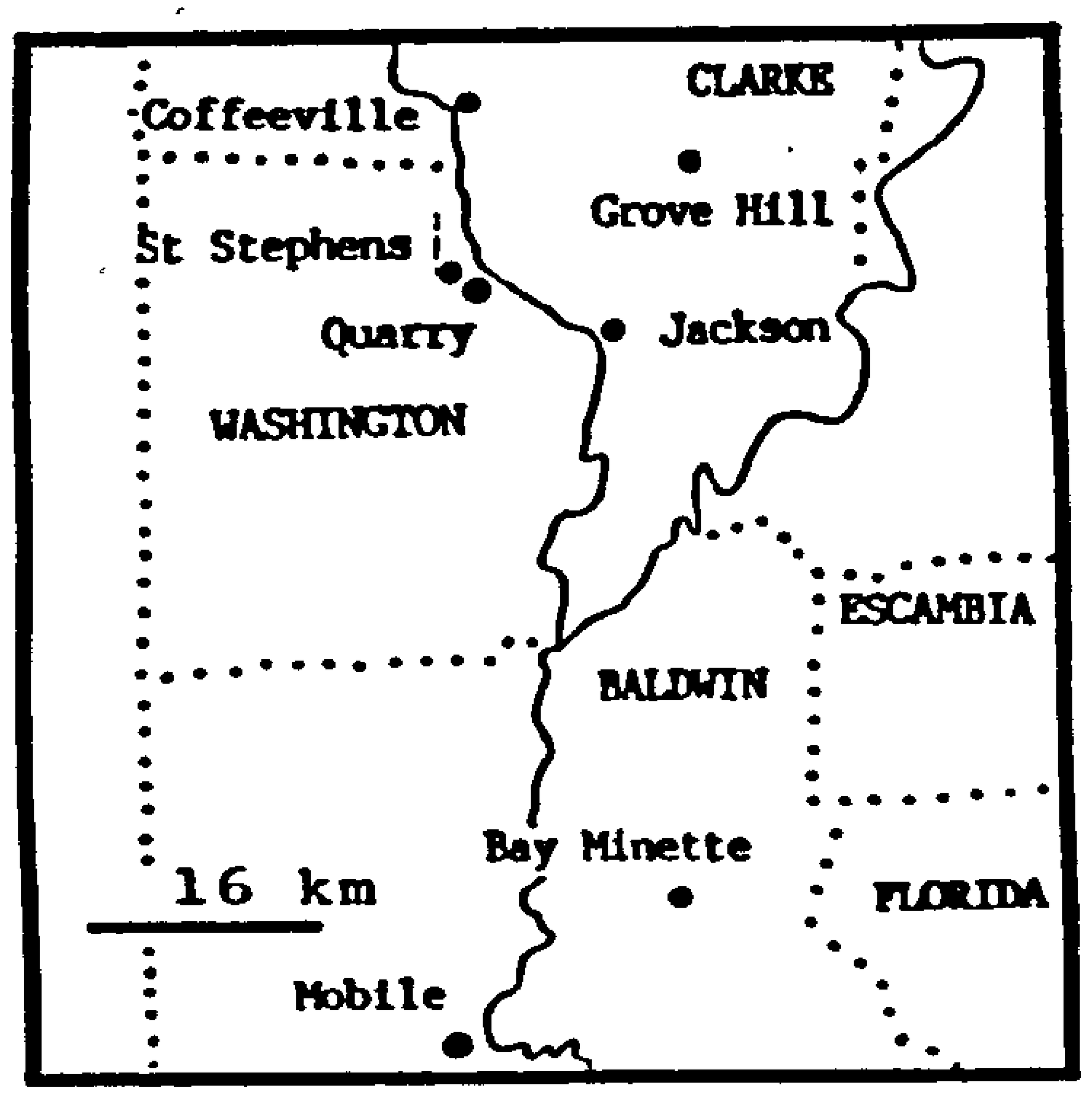
One of the most complete and continuously exposed marine Oligocene sections in North America is exposed in this quarry (Mancini and Copeland, 1986). The geological section includes over 14 feet (4m) of Upper Eocene, Jackson stage (Priabonian) strata and about 160 feet (49m) of Oligocene, Vicksburg and Chickasaway stages (Stampian and Chattian) section. The Eocene - Oligocene contact is excellently preserved in the north (Pelham Hill) quarry.

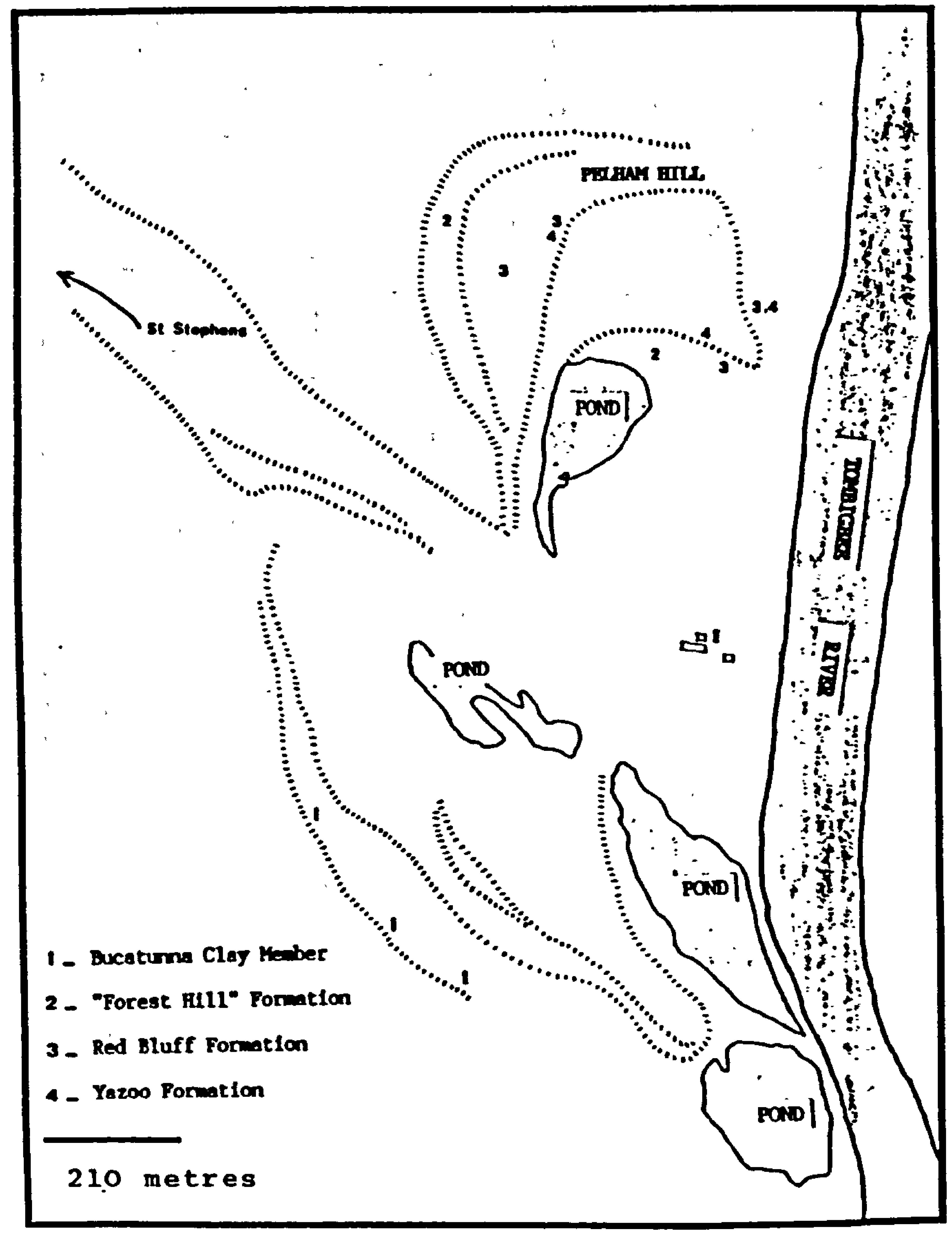
The samples studied (see lithological log in Fig.32.) were collected and provided by Dr A.R.Lord. These samples were analysed in order to compare and contrast the known Eocene and Oligocene assemblages of this locality with those from the North Sea. In addition, many species of Reticulofenestra have their type locality here, therefore, as a special study of this genus was undertaken it was considered expedient to look at this section.

#### 1.6.2.2 Hampden Beach and William's Bluff (near Oamaru), New Zealand -

Hampden Beach lies approximately 29 kilometres south of Oamaru, and 37 kilometres north of Dunedin on the east coast of South Island New Zealand. William's Bluff lies 12 kilometres north-east of Oamaru (see Fig.16.). The

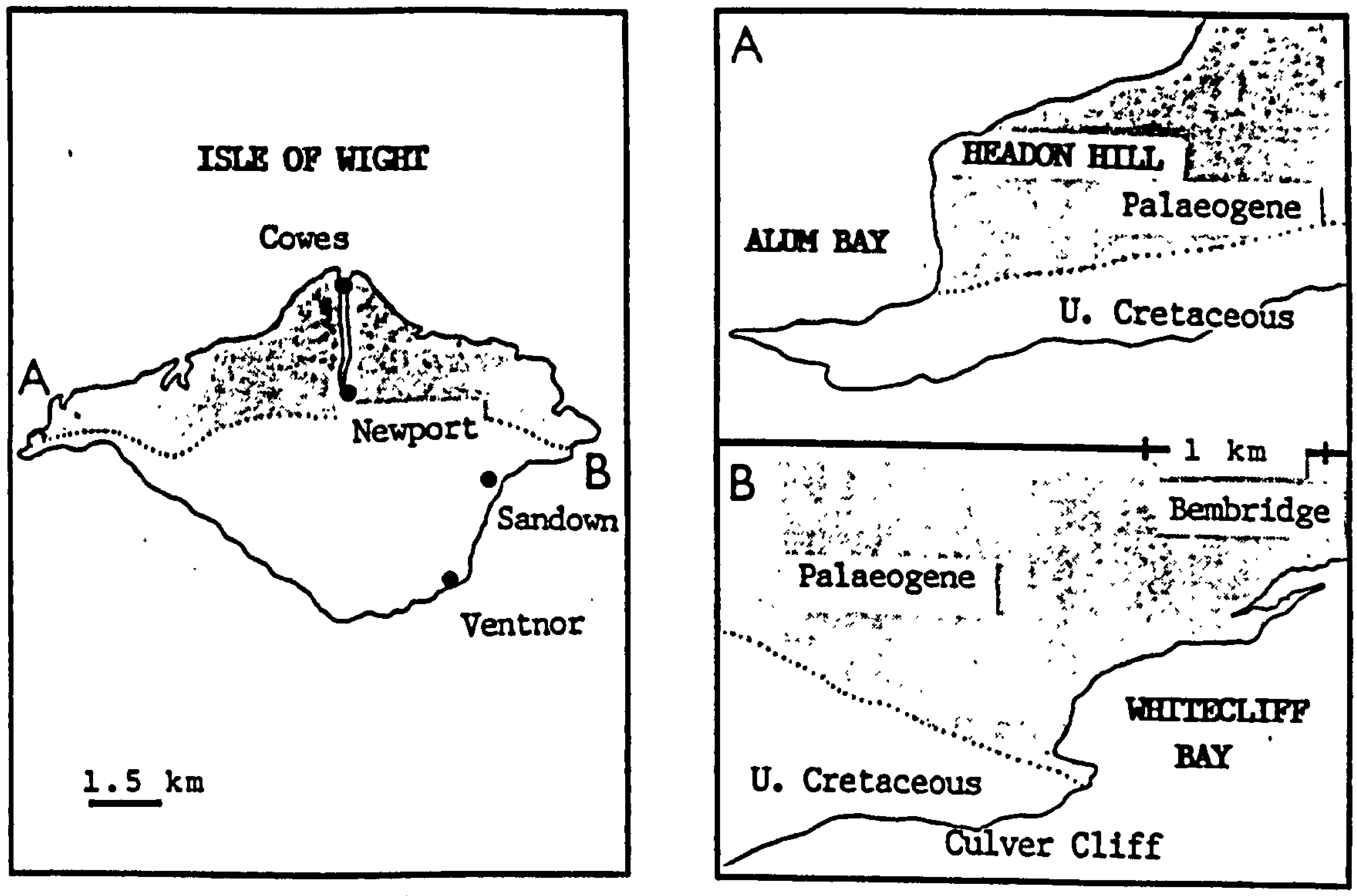


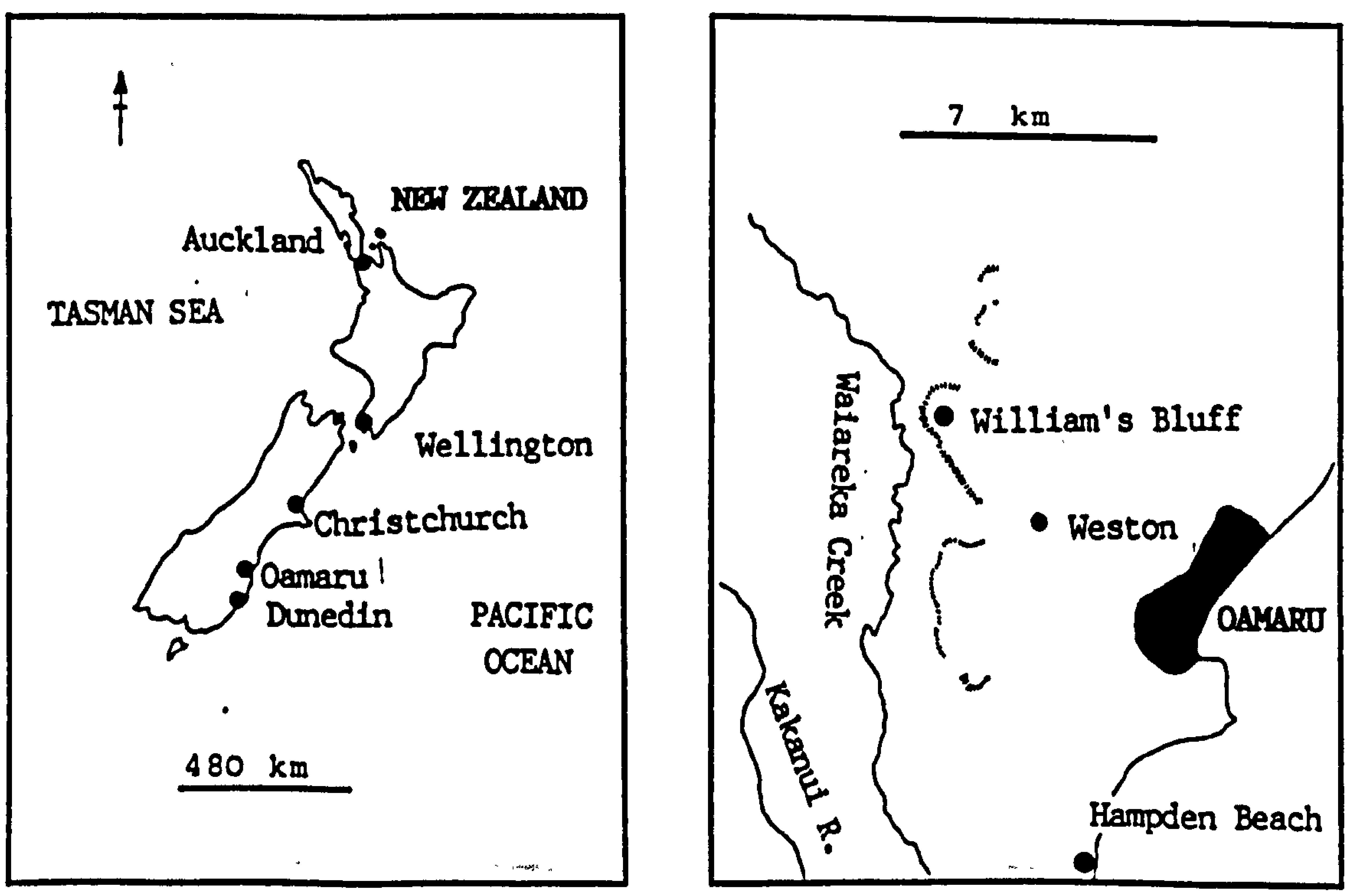




Location maps for St. Stephen's Quarry, Alabama, U.S.A. (re-drawn in part from Mancini and Copeland, 1976). FIG 15.

FIG. 16.




Sample locality maps



Bortonian (Eocene) material collected and kindly provided by Dr.D.B. Waghorn was of value because firstly, it provided comparative material for Reticulofenestra hampdenensis Edwards, and many other Reticulofenestra species and, secondly, it enabled a comparison to be made with the similarly high-latitude North Sea Eocene material.

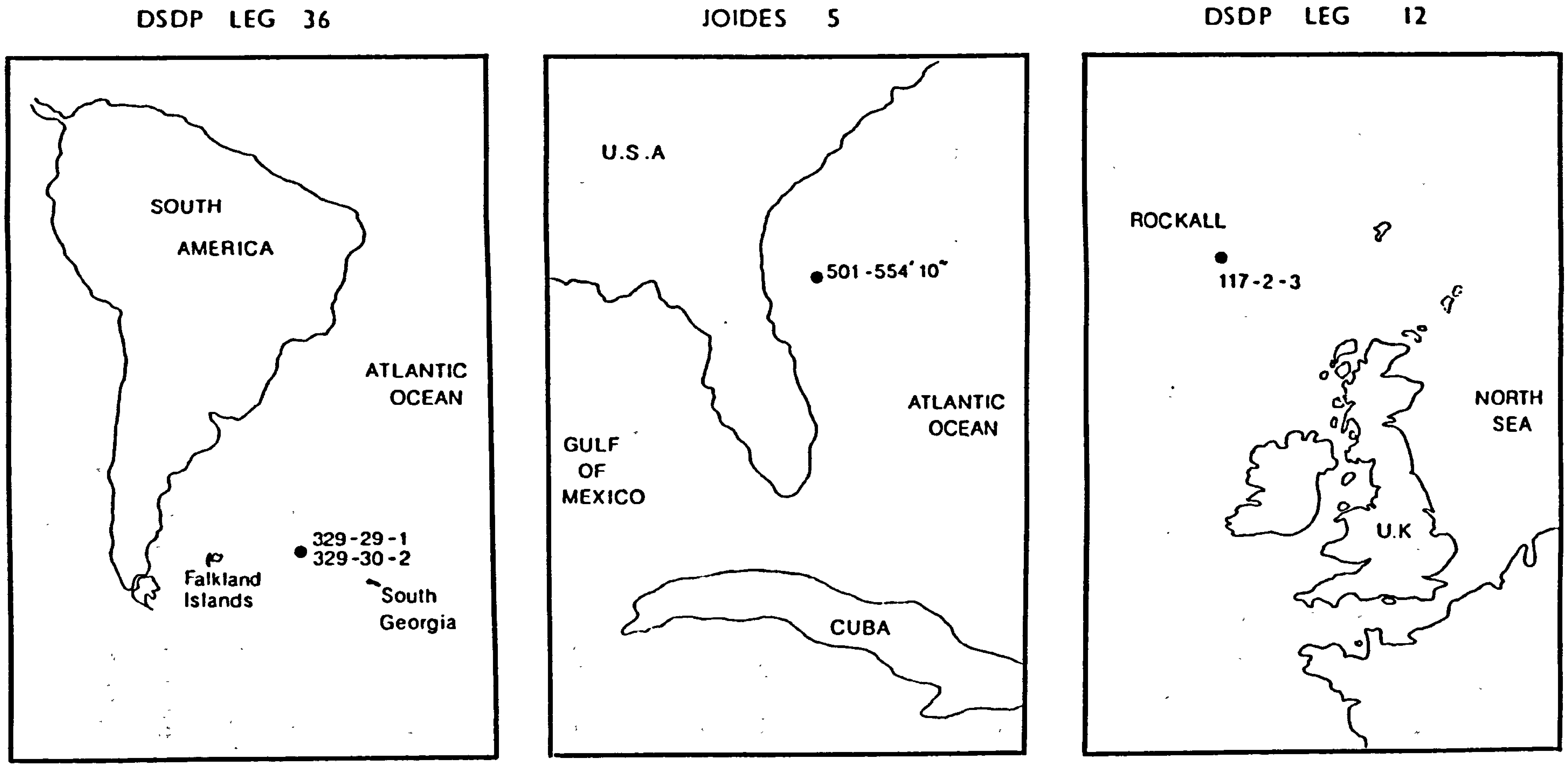
**1.6.2.3 JOIDES 5 (J501), Blake Plateau, 554'10" below top -**

In 1965 a number of cores were drilled on the Blake Plateau, on the Florida continental shelf, as part of the JOIDES Deep Earth Sampling Programme (see Fig.17). A sample from hole 5 (J501) at a depth of 554' 10" below the sea floor was kindly supplied by Prof. H.R. Thierstein from the thesis collection of Dr. P.H. Roth as a reference sample for Cyclicargolithus floridanus. It also provided a good Oligocene assemblage which could be compared with those recovered from the North Sea Basin.

**1.6.2.4 XXth European Micropalaeontological Colloquium : Palaeogene of the Isle of Wight -**

The XXth European Micropalaeontological Colloquium took place in Great Britain (Dorset and the Isle of Wight) during early September 1987. A number of samples from Whitecliff Bay, Alum Bay and Headon Hill on the Isle of Wight were examined during production of the Field Guide for the colloquium (see Fig.16). This suite of samples was collected and provided by Prof.J.W.Murray and provided an opportunity to study the Tertiary section from the Hampshire Basin, which was an extension of the southern North Sea Basin at the time. (see Figs.34,35 and 36 for schematic lithological sections)

**1.6.2.5 DSDP Leg 36 Site 329 (50°39.31'S,46°05.73'W) and DSDP Leg 12 Site 117 (57°20.17'N,15°23.97'W) -** Site 329 is located in the South Atlantic Ocean,




Sample location maps.

FIG. 17.

approximately 800 kilometres east of the Falkland Islands and 640 kilometres north-west of South Georgia (see Fig.17.). Site 117 is situated in the North Atlantic Ocean, on the boundary between the Hatton-Rockall Basin and Rockall Bank (see Fig.17.), some 320 kilometres north west of Scotland. Both of these high-latitude sites were primarily selected for the abundant presence of Chiasmolithus altus, which enabled comparisons to be made with specimens found in the North Sea Basin material. These samples also afforded a further opportunity to compare well-preserved examples of Cyclicargolithus abisectus and Cyclicargolithus floridanus. (See Figs.37 and 38 for lithological logs).

**1.6.2.6 London Clay Formation, north-central London -**

The outcrop of this unit is limited in area, particularly in the 'urbanised' region of Greater London (see Fig.18.) For this reason opportunities to study the London Clay Formation in, or near, London have been very limited. Temporary exposures have become the only reasonable means of access and it was fortunate that major excavations at Parliament Hill Fields, Kings Cross, and other isolated points in London (see Fig.19.) occurred during the course of this study, providing deep workings and facilitating the collection of unweathered samples. It was hoped that detailed analysis of the London Clay Formation will provide an insight into the calcareous nannoplankton of Early Eocene times in the restricted environment of the London Clay Sea. The new excavations provided an opportunity to examine these beds for the first time for calcareous nannofossils, and for the first time using modern microscopic equipment. The study material was collected and donated by Dr. J.E. Robinson.

**1.6.2.7 Pegwell Bay, Kent -**

Some samples from the Pegwell Bay section in Kent (see Fig.20.) were analysed. One sample was donated by Prof. D. Curry, from the Crepidula Band and a

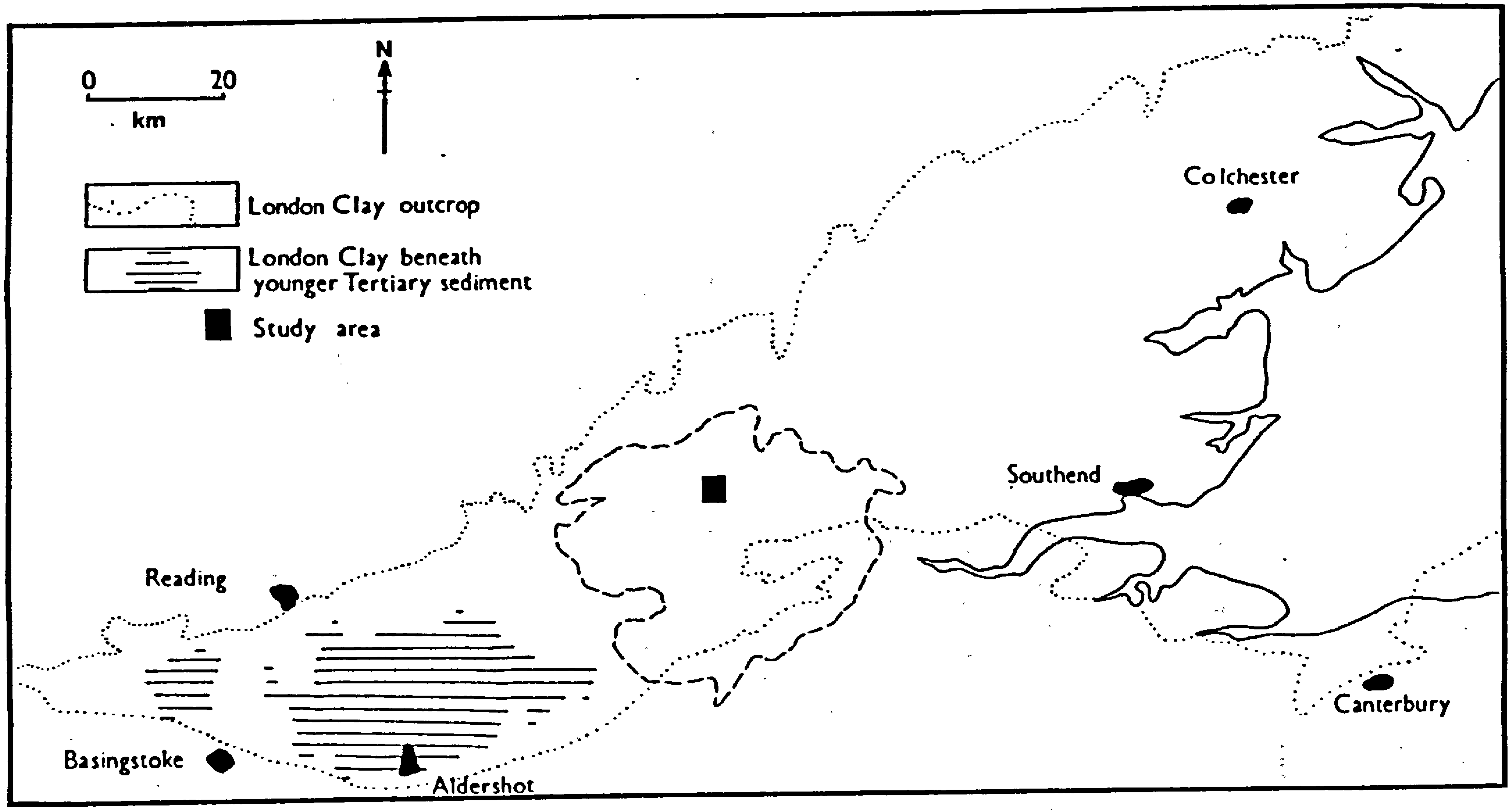
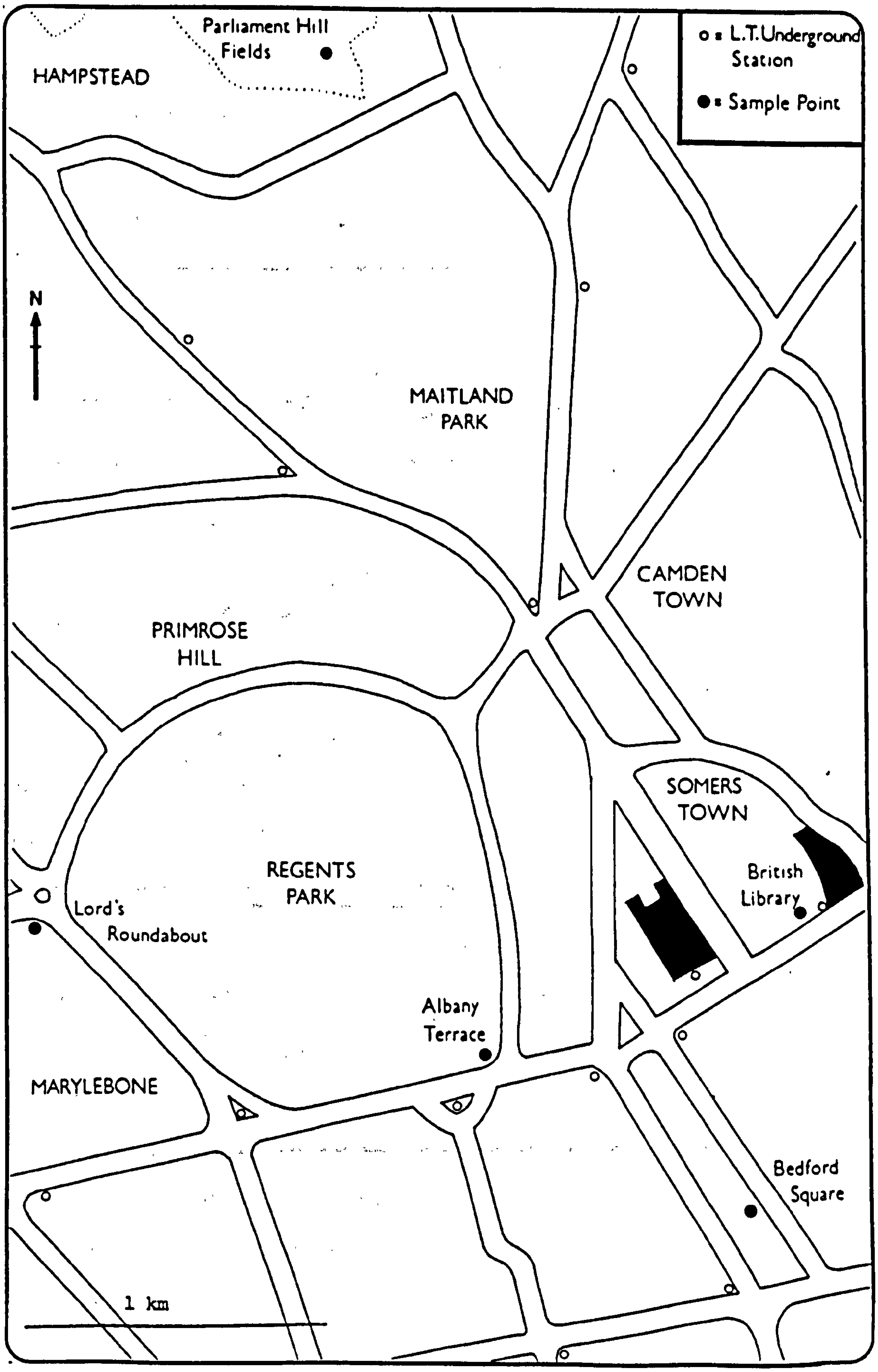



FIG. 18.

Distribution of the London Clay Formation in the London Basin.

Re-drawn from King (1981).

FIG.19 .




London Clay Formation sample localities in the north London area.

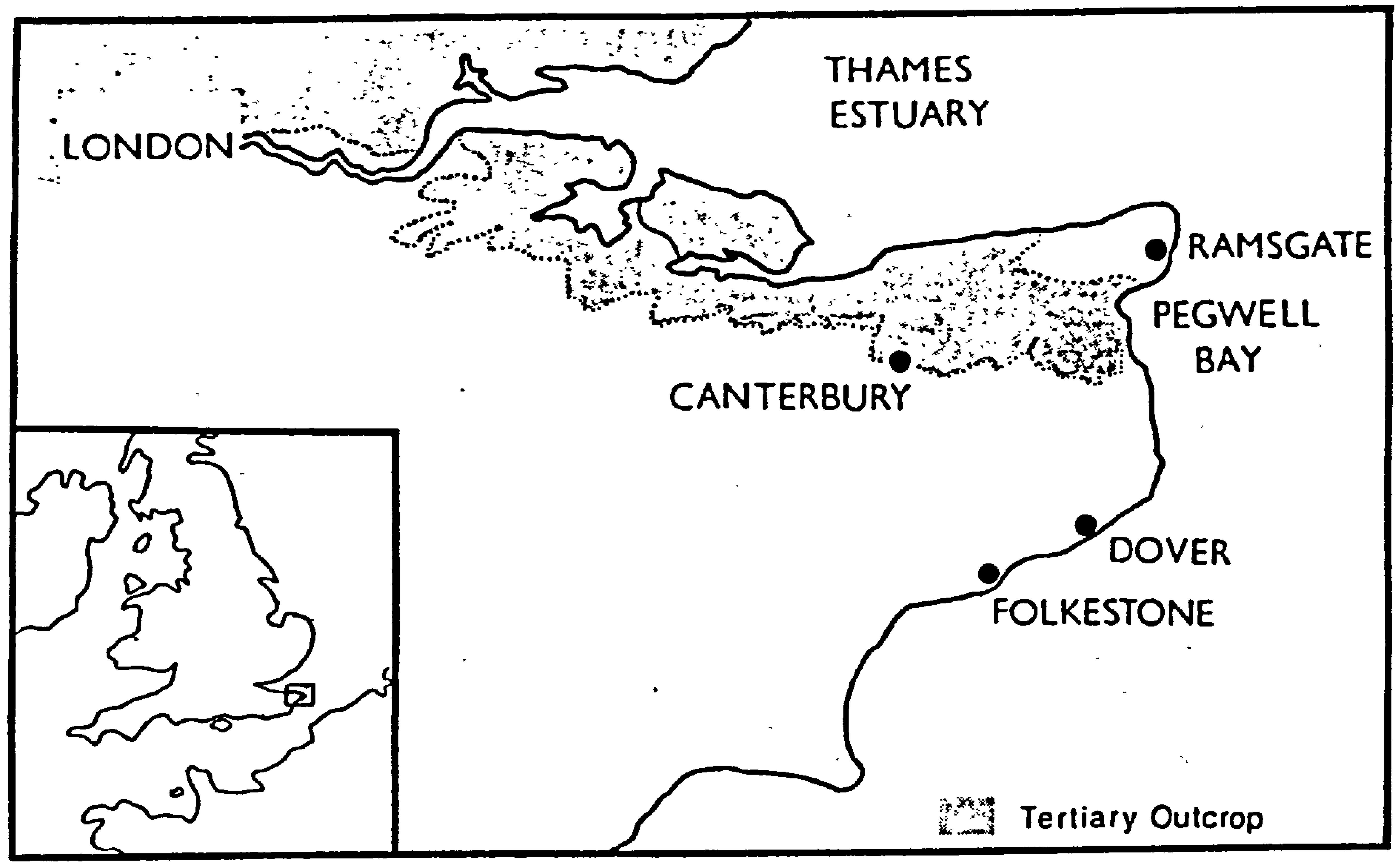



FIG. 20.

Pegwell Bay - Locality map.

number of other samples were collected and previously studied by A.Godfrey for an M.Sc project. These Late Palaeocene samples were seen to be of an age between that of the Palaeocene and Eocene assemblages found in the North Sea Basin.(see Fig.39 for lithological log).

### 1.6.3 SAMPLING OF STUDY MATERIAL :

**1.6.3.1 Sampling Strategy** - The well material was made up essentially of two kinds of sample;

i. Side Wall Sample (SWS) : a miniature core (approximately 1"x3") is taken from the side wall of the hole by firing a hollow 'bullet casing' into the rock (depth accurate to within 1 or 2 feet).

ii. Ditch Cuttings Sample (DC) : these samples comprise the rock chippings which are returned to the surface in the drill mud after the drill head has penetrated a particular stratum (accurate to between 10 and 30 feet depending on the speed of drilling and casing levels).

The advantage of using SWS's is that they have a uniform lithology and a precise position in the well, however, their distribution is often too widely spaced for refined calcareous nannofossil analysis, or concentrated around sand bodies and therefore of limited use. DC's on the other hand may represent a variety of lithologies covering a wide interval (dependant upon the frequency of collection at the well head). Invariably the study of a well must involve both types of sample: using DC's to cover broad intervals and SWS's to pinpoint boundaries etc.

1.6.3.2 **Sample selection** - Selection of the position and number of individual samples from within a well depended largely upon the distribution and availability of Side Wall Samples (SWS), as well as the distribution and extent of each formation and its characteristic lithology. Sample levels are marked on the lithological columns in Appendix 1. The total number of samples taken, and analysed, per well is listed below :

| WELL NUMBER | SWS | + | DC | + | TOTAL |
|---|---|---|---|---|---|
| 29/10-1 | 104 | | 100 | | 204 |
| 21/11-1 | 37 | | 114 | | 151 |
| 21/30-1 | 81 | | 14 | | 95 |
| 29/3-1 | 35 | | 0 | | 35 |
| 49/9-1 | 25 | | 8 | | 33 |
| 16/8-1 | 34 | | 10 | | 44 |
| 14/29-1 | 17 | | 18 | | 35 |
| 29/7-1 | 27 | | 16 | | 43 |
| 30/6-2 | 10 | | 27 | | 37 |
| 30/19-2 | 26 | | 17 | | 43 |
| 49/10-1 | 6 | | 8 | | 14 |
| 49/19-1 | 0 | | 5 | | 5 |
| | 402 | | 337 | | 739 |

The sample levels of the comparative material appear on the respective lithological logs. The total number of samples taken, and analysed, per locality is listed below :

| LOCALITY | SITE | TOTAL |
|---|---|---|
| London Clay | Parliament Hill | 8 |
| | British Library | 5 |
| | Lord's Roundabout | 1 |
| | Bedford Square | 1 |
| | Albany Terrace | 1 |
| Alabama | St Stephens Quarry | 11 |
| New Zealand | Hampden Beach | 10 |

| | | |
|---|---|---|
| | William's Bluff | 1 |
| Blake Plateau | JOIDES 5 (J501) | 1 |
| Hampshire Basin | Isle of Wight | 22 |
| Kent | Pegwell Bay | 6 |
| DSDP 36 | Site 329-30-2 | 1 |
| | Site 329-29-1 | 1 |
| DSDP 12 | Site 117-2-3 | 1 |
| | | 70 |

### 1.6.4 PREPARATION OF STUDY MATERIAL :

**1.6.4.1 Review of preparation methodology** - Ever since the 1950's, when calcareous nannofossils first began to be routinely examined, a great number of techniques for liberating these microfossils from sediment have been described, as have an equally large number of methods for transferring these assemblages to glass slides, etc. The choice of preparation technique is largely determined by the operator's needs, the time and facilities available, etc. Taylor and Hamilton (1982, p.12) give a good review of some of the preparation techniques which have been used in the past and for further elaboration the reader is directed to Backman (1980, p.6), Haq (1966, p.27), Hay (1977) and Perch-Nielsen (1985, p.330).

**1.6.4.2 Preparation techniques** - In order to study the calcareous nannofossil assemblage within a sample that sample must first be crushed (to facilitate separation of the microfossils from the host sediment) and then prepared and mounted in order that the assemblage can be viewed.

A number of preparations may be used on any one sample, depending on the requirements of the researcher. Basically, four types of preparation technique were employed during this study. These are outlined below.

i. Quick Smear Slide (see Table.4.) - This method enabled samples to be prepared and ready for analysis in less than five minutes. It has , therefore, the advantage of being exceptionally rapid, but the assemblage is often poorly distributed across the slide and rarely fully liberated from the host sediment. It is recommended that this method be used for rapidly checking if a sample is fossiliferous and as a control for density/diversity before moving onto a more sophisticated technique for routine analysis.

ii. Smear slide (see Tables 4. and 5.) - Smear slides were prepared for all the sample levels used in this study. Two methods of producing smear slides were employed at the outset of the project, but it soon became apparent that the 'UCL' method had advantages over the 'Industrial' method :

a. No need for ultrasound treatment.

b. No shared equipment i.e. Pestel and mortar, copper gauze.

c. More reliable mounting medium.

A number of different mounting media were utilised during the course of this research for adhering the cover slips to the smear slides. A discussion of their relative merits follows;

a. Canada Balsam : Used extensively without a fume cupboard at Shell U.K. laboratory. Easily handled, but prone to bubbling and discoloration when overheated, and does not set hard if underheated.

Table 4.

## QUICK SMEAR METHOD

i. Scrape the cleaned surface of the sample with a knife so that a fine powder of sediment falls onto a glass slide.

ii. Disperse the residue evenly across the glass slide using a glass rod or toothpick and a little distilled water.

iii. The slide can be permanently mounted, see smear slide method, or temporarily mounted using a drop of immersion oil between the glass slide and the cover slip.

## 'UCL' METHOD

i. Crush sample and place a small amount in a glass beaker. Add a dilute solution of Sodium hexametaphosphate and allow to stand overnight.

ii. Stir suspension then put a few drops, using a pipette,of it onto a glass slide and spread out evenly.

iii. Dry the slide on a hot-plate and then add a single drop of mounting medium ('Petrapoxy 154'). Heat the slide and place a glass cover slip on top of the slide.

iv. Allow the slide to stand at approximately 100°C for five minutes and then cool before viewing.

Table. 5

## INDUSTRIAL METHOD

i. Grind sample to a fine powder using a pestle and mortar. Put the granules into a test tube and add a little distilled water.

ii. Place the test tube in an ultrasonic bath for 45 seconds.

iii. Rinse the contents of the tube through a copper gauze using distilled water.

iv. Allow suspension to stand for 45 minutes.

v. Decant excess water to leave sediment pellet. Using a glass rod spread some of the pellet over the surface of a cover slip.

vi. Allow the cover slip to dry on a hot-plate before placing it on a glass slide which has a drop of Canada Balsam on it.

vii. Heat the glass slide until the Canada Balsam bubbles and has dispersed evenly across the slide.

viii. Allow the slide to cool before viewing.

## CENTRIFUGE METHOD

i. As for 'UCL Method' step i.

ii. Place suspension in a test tube and centrifuge it at 300 rpm for 15 seconds.

iii. Reject pellet and retain supernatant for further centrifuging at 1000 rpm for 30 seconds.

iv. Reject supernatant and retain pellet. Re-suspend pellet using distilled water and centrifuge at 1000 rpm for 30 seconds.

v. Repeat step iv. until the supernatant is translucent. Proceed from 'UCL Method' step ii.

Table 6.

SEM STUB PREPARATION

i. Follow Centrifuge Method until step v., then dilute the final suspension with distilled water until it becomes almost transparent.

ii. Put a few drops onto a circular cover slip (13mm diameter) and allow to dry.

iii. Cover an SEM stub with colloidal silver and place the dried cover slip on top. Allow to dry.

iv. Coat stub surface with gold or other conductive medium and view in a scanning electron microscope.

b. Canada Balsam with Xylene : Used only in a fume cupboard, an expensive but hard-setting agent. However, Xylene is a suspected carcinogen, thus the use and handling of this medium is discouraged.

c. 'DPX' : A clear, viscous medium which proved very difficult to use. The use of a fume cupboard was necessary, and even strict heat regulation could not produce a hard-set without bubbles.

d. Glycerol Jelly : Widely used in industry, easy and safe to use, but does not set hard. This medium, therefore, is unsuitable for 'permanent' mounts even if the edges of the cover slip are sealed.

e. 'Petrapoxy 154' : Safe and easy to use, very few problems with bubbling. This mounting medium produced hard-setting slides without discoloration and proved to be the best of those analysed. There have been some doubts expressed as to it its permanency; it has been suggested that it may deteriorate with time and as a result etch assemblages, however, no evidence for such deterioration has been found during the course of this study.

Generally smear slides give a good distribution of the assemblage across the slide. Individual specimens tend to be 'clean' (preservational effects notwithstanding) and readily identifiable.

iii. Centrifuge slides/Scanning electron microscope stubs (see Tables.5 and 6.) - Centrifuge slides were not routinely made in the course of this study as the type of sediment predominantly encountered (mudstone/claystone) does not necessitate its use. However, in specific cases, it was necessary to 'clean' the assemblages (usually in chalks) for a better view of the constituent microfossils.

This technique was, however, routinely used in the preparation of samples for viewing in the scanning electron microscope. The removal of clay-sized particles and large pieces of detritus is essential for a good scanning electron microscope image and clean specimens.

iv. Same-specimen Technique (see Fig.21) - The study of individual calcareous nannofossil specimens in both the light microscope (LM) and the scanning electron microscope (SEM) is not a new idea and a number of papers have been published on the subject. However, it is a much neglected aspect of routine calcareous nannofossil analysis and one which deserves a much wider application.

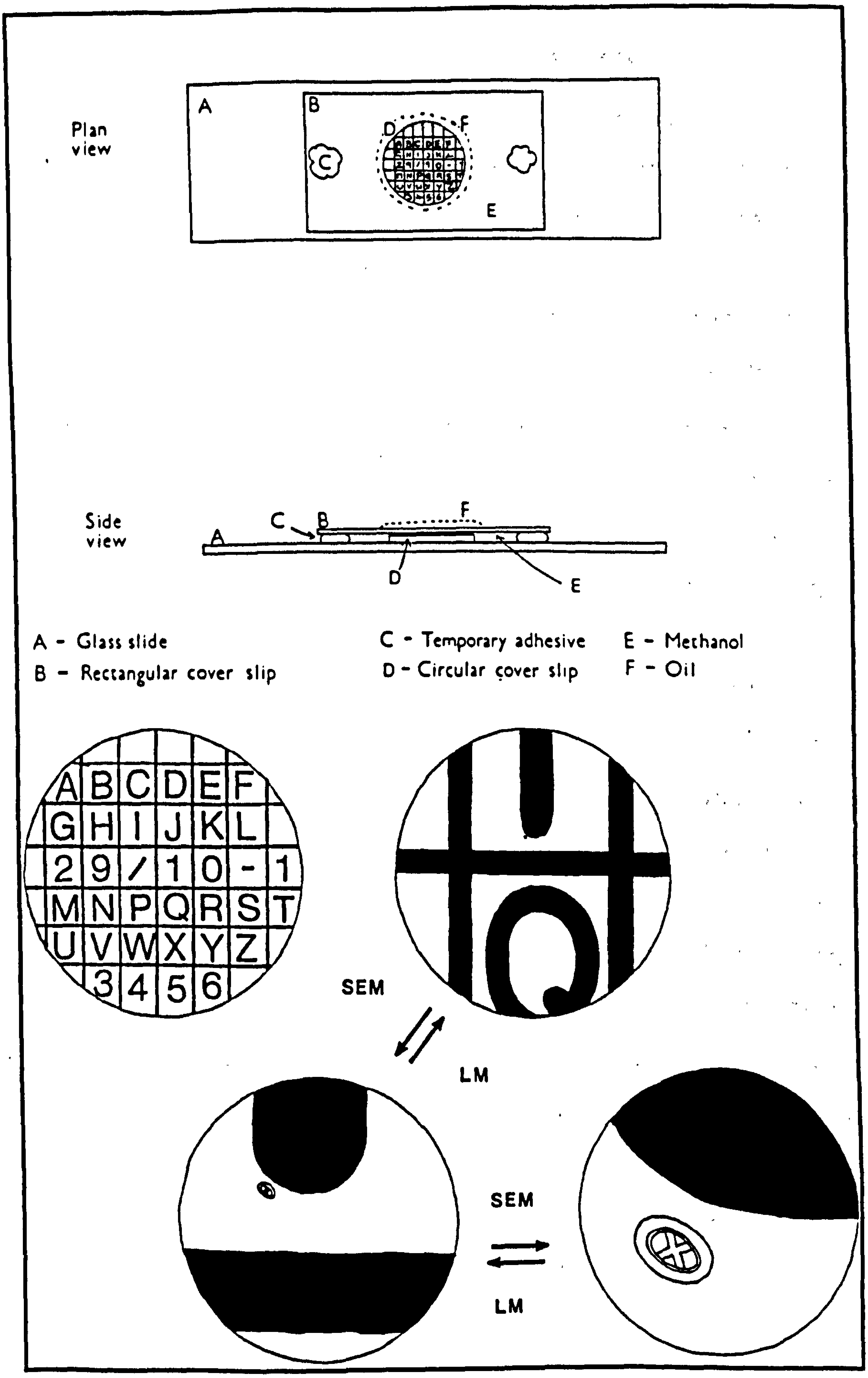
These two microscopical media complement one another and it is desirable to examine individual specimens using both.

Previous attempts to study the same specimen in the LM and the SEM (Perch-Nielsen, 1967a; Thierstein et al., 1971; Sherwood and Levin, 1973; Moshkovitz, 1974 & 1978) have involved the use of materials and equipment not usually employed in nannopalaeontology, and necessitated specialist techniques and sometimes complex calculations methodology.

A technique by which the same specimen may be viewed in both the LM and the SEM is clearly beneficial for the elucidation of taxonomic problems. Such a method, which is clean, rapid and accurate, utilising routine materials, and, therefore, inexpensive, is of considerable interest. Just such a technique was developed by Gallagher (1988) and is summarised below.

**Preparation of cover slip** - A circular cover slip (13mm diameter) is used and in order that the position of individual specimens within the assemblage dispersed onto its surface can be accurately recorded it is necessary to have an annotated grid on the cover slip which will be visible in both the LM and the SEM. It is possible to etch the surface of the cover slip with a diamond-tipped pen or

FIG. 21.




Slide configuration (top) and procedure for viewing in the LM and SEM (bottom) for same specimen technique.

Hydrofluoric acid to produce negative relief, but the fragile cover slip is easily damaged in this way. The simplest method of applying the grid is to draw it on with a standard technical pen (0.1mm nib). In this way the grid lines and labels of any configuration can be produced to suit the investigators needs. The ink shows up as dark lines in the LM and as raised ridges beneath the conductive coating in the SEM (see Fig.21).Once a circular cover slip has been prepared in this way and allowed to dry for a few minutes , some drops of the sample solution (see centrifuge method in Table.5.) are applied to the upper surface and it is dried at 100°C for 15 minutes.

**Viewing in the LM** (see Fig.21) - The circular cover slip is placed on to a large rectangular glass slide (75mm x 25mm) and covered with a rectangular cover slip (40mm x 22mm). The rectangular cover slip is held in place with re-usable adhesive (e.g. 'blu-tack') to prevent the circular cover slip from moving during analysis. Methanol is introduced to the void between the glass slide and the rectangular cover slip for better penetration of the transmitted light. If oil immersion lenses are used, a drop of immersion oil can be placed on the upper surface of the rectangular cover slip. The position of individual specimens is readily recorded by reference to the grid.

**Viewing in the SEM** (see Fig.21) - After LM analysis the rectangular cover slip is carefully removed and discarded, allowing the methanol to evaporate from the surface of the circular cover slip on which the calcareous nannofossil assemblage is dispersed. The circular cover slip is placed on an SEM stub (see SEM stub method in Table.4.) and viewed as normal in the SEM.

Using a technique for viewing the same specimen in both the LM and the SEM is expedient for a number of reasons, e.g. the exact nature of central area characteristics such as grills, bars and spines, etc., which may be obscure or indistinct in the LM can be determined using the SEM. Also specimens greatly altered by diagenetic effects may be identified by a combination of their LM and SEM characteristics (see Plates A-D). Finally, and perhaps most importantly, such a technique provides an opportunity to describe new forms in the most complete way yet possible, thus minimising the misinterpretation of morphological features of taxonomic significance as an artefact of the instrumental viewing medium.

### 1.6.5 OBSERVATION OF STUDY MATERIAL :

1.6.5.1 **Light Microscope** - Routine phase contrast and cross-polarised light observations were made using an Olympus BHT-112 optical microscope with X10, X40 (plane and phase contrast) and X100 (plane and phase contrast; both oil immersion) objectives and a X10 eyepiece (graticule fitted for approximate measurements). A Vernier stage scale enabled specimens to be relocated relatively accurately by using six figure grid references.

Photomicrographs were produced on Carl Zeiss Mark I and Mark II photomicroscopes. Specimens located in the Olympus microscope could be relocated in the Carl Zeiss photomicroscope with the aid of an 'England Finder' grid.

1.6.5.2 **Scanning electron microscope** - A Jeol T200 scanning electron microscope was used to produce high definition images of calcareous nannofossils and detailed photomicrographs. The transfer of specimens from LM to SEM observation is discussed above.

## PLATE A : SAME SPECIMEN TECHNIQUE

LM = Light microscope SEM = Scanning electron microscope

1,5 & 9 Heliolithus riedelii Bramlette and Sullivan : Fig.1 UCL-2426-26 LM crossed-nicols; Fig.5 UCL-2426-27 LM phase contrast; Fig.9 UCL-2433-03 SEM, side view of a well preserved specimen. AG16. Pegwell Bay, Kent. Late Palaeocene. X3,350.

2,6 & 10 Reticulofenestra umbilicus (Levin) Martini and Ritzkowski : Fig.2 UCL-2392-05 LM crossed-nicols; Fig.6 UCL-2392-06 LM phase contrast; Fig.10 UCL-2423-05 SEM, proximal view, relic of a fine central area grill visible. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X4,450.

3,7 & 11 Ericsonia formosa (Kamptner) Haq : Fig.3 UCL-2392-01 LM crossed-nicols, good extinction figure but no rim detail; Fig.7 UCL-2392-02 LM phase contrast; Fig.11 UCL-2423-02 SEM, distal view, elements clearly defined though slightly overgrown in the central area. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X4,450.

4,8 & 12 Pontosphaera multipora (Kamptner) Roth : Fig.4 UCL-2392-23 LM crossed-nicols, good image of pores and extinction figure, but no indication of direction of view; Fig.8 UCL-2392-25 LM phase contrast; Fig.12 UCL-2423-17 SEM, distal view of a slightly etched specimen. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X4,450.

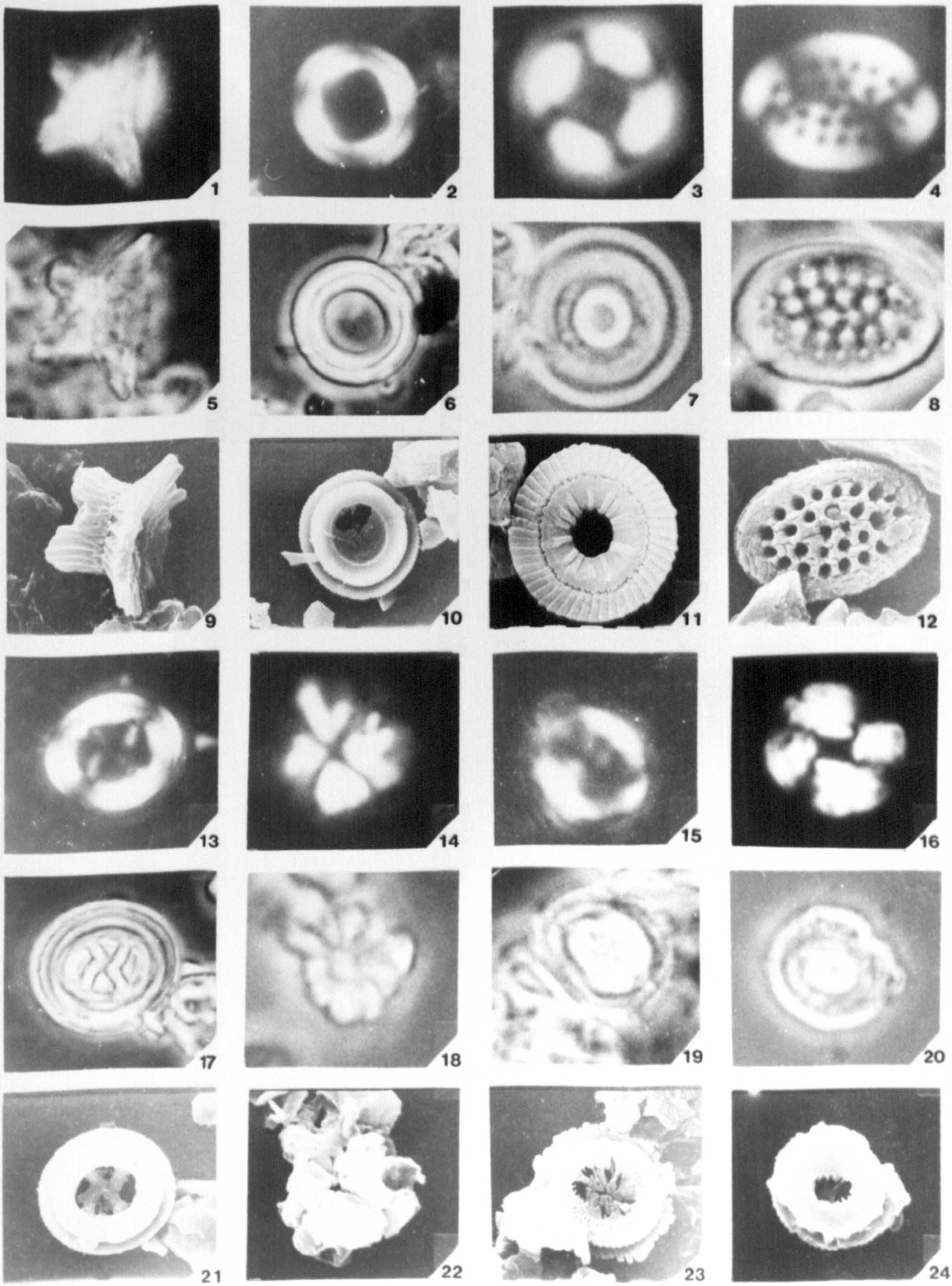
13,17 & 21 Chiasmolithus solitus (Bramlette and Sullivan) Locker : Fig.13 UCL-2392-09 LM crossed-nicols; Fig.17 UCL-2392-10 LM phase contrast; Fig.21 UCL-2423-11 SEM, proximal view of a well preserved specimen. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X2,230.

14,18 & 22 Sphenolithus moriformis (Brönniman and Stradner) Bramlette and Wilcoxon : Fig.14 UCL-2644-14 LM crossed-nicols; Fig.18 UCL-2644-15 LM phase contrast; Fig.22 UCL-2658-02 SEM, very poor preservation. Shell/Esso North Sea well number 49/10-1, depth 2400'. Middle Eocene. X6,700.

15,19 & 23 Toweius tovae Perch-Nielsen : Fig.15 UCL-2426-32 LM crossed-nicols; Fig.19 UCL-2426-31 LM phase contrast; Fig.23 UCL-2433-06 SEM, proximal view, good central area grill preservation. AG16. Pegwell Bay, Kent. Late Palaeocene. X4,450.

16,20 & 24 Reticulofenestra dictyoda (Deflandre and Fert) Stradner : Fig.16 UCL-2644-16 LM crossed-nicols; Fig.20 UCL-2644-18 LM phase contrast; Fig.24 UCL-2658-03 SEM, proximal view of an etched specimen. Shell/Esso North Sea well number 49/10-1, depth 2400'. Middle Eocene. X4,450.

# PLATE A



## PLATE B : SAME SPECIMEN TECHNIQUE

LM = Light microscope SEM = Scanning electron microscope

1,5 & 9 Pemma basquensis (Martini) Báldi-Beke : Fig.1 UCL-2643-01 LM crossed-nicols; Fig.5 UCL-2643-02 LM phase contrast; Fig.9 UCL-2649-32 SEM, broken specimen. Shell/Esso North Sea well number 49/10-1, depth 2400'. Middle Eocene. X3,350.

2,6 & 10 Helicosphaera recta Haq : Fig.2 UCL-2386-17 LM crossed-nicols; Fig.6 UCL-2386-15 LM phase contrast; Fig.10 UCL-2391-30 SEM, proximal view of a well preserved specimen. JOIDES Hole 5, 554' 10" below top. Early Oligocene. X2,230.

3,7 & 11 Discoaster tanii Bramlette and Riedel : Fig.3 UCL-2644-27 LM crossed-nicols; Fig.7 UCL-2644-28 LM phase contrast; Fig.11 UCL-2658-11 SEM, extremely poorly preserved. Shell/Esso North Sea well number 49/10-1, depth 2400'. Middle Eocene. X3,350.

4,8 & 12 Pontosphaera multipora (Kamptner) Roth : Fig.4 UCL-2637B-09 LM crossed-nicols; Fig.8 2637B-10 LM phase contrast; Fig.12 UCL-2649-23 SEM, proximal view. Shell/Esso North Sea well number 29/10-1, depth 5796'. Early Miocene. X4,450.

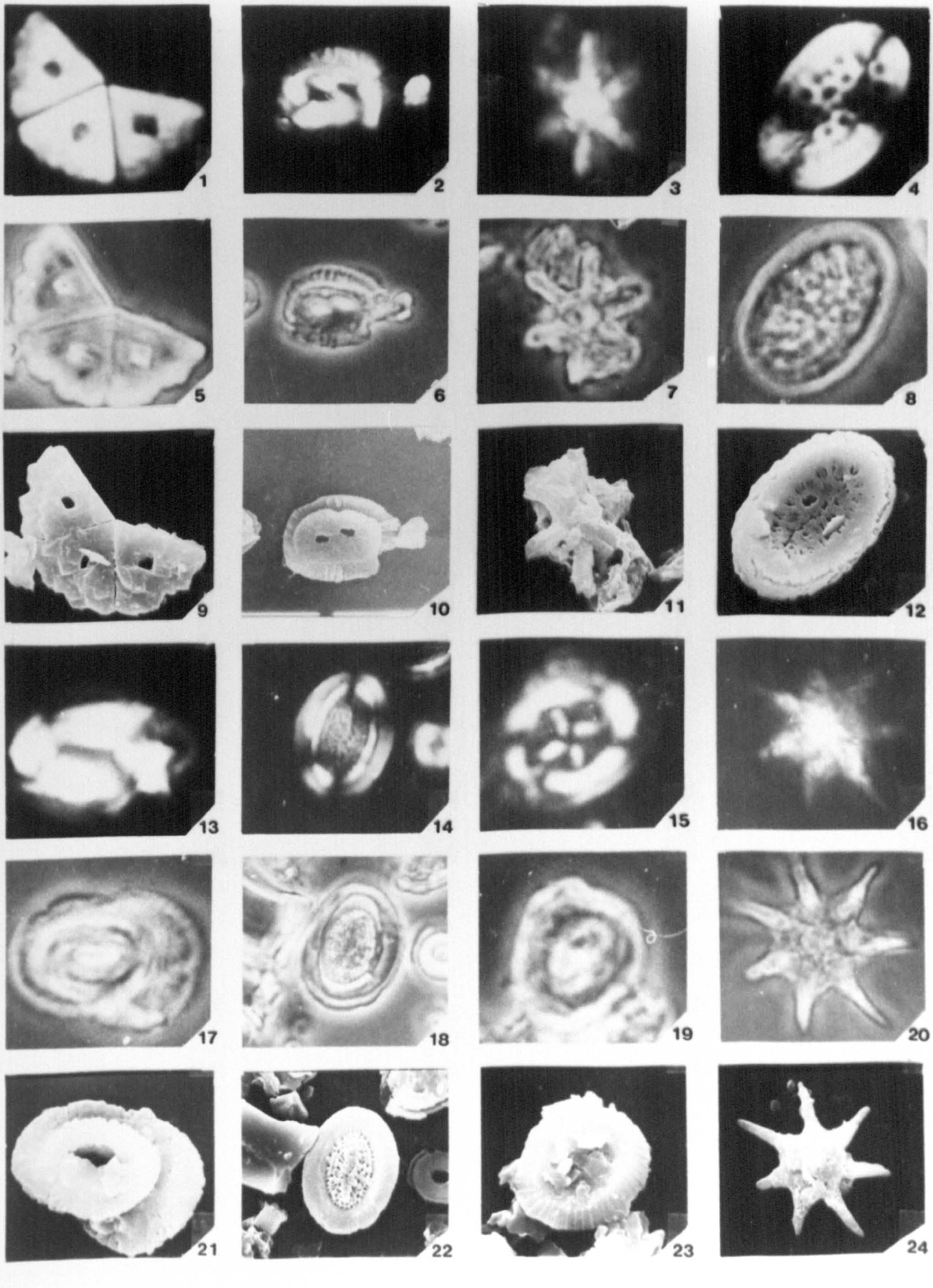
13,17 & 21 Helicosphaera ampliaperta Bramlette and Wilcoxon : Fig.13 UCL-2637B-08 LM crossed-nicols; Fig.17 UCL-2637B-07 LM phase contrast; Fig.21 UCL-2649-22 SEM, proximal view of a well preserved specimen. Shell/Esso North Sea well number 29/10-1, depth 5796'. Early Miocene. X4,450.

14,18 & 22 Reticulofenestra onusta (Perch-Nielsen) Wise : Fig.14 UCL-2585-23 LM crossed-nicols, good birefringence and clear central area grill; Fig.18 UCL-2585-24 LM phase contrast, clear central area grill; Fig.22 UCL-2601-04 SEM, distal view, tube cycle absent, central area grill slightly overgrown. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene. X2,230.

15,19 & 23 Cruciplacolithus tenuis (Stradner) Hay and Mohler : Fig.15 UCL-2648-13 LM crossed-nicols; Fig.19 UCL-2648-14 LM phase contrast; Fig.23 UCL-2658-20 SEM, overgrown specimen. Shell/Esso North Sea well number 30/6-2, depth 9700'. Early Palaeocene. X4,450.

16,20 & 24 Discoaster lodoensis Bramlette and Riedel : Fig.16 UCL-2637-01 LM crossed-nicols; Fig.20 UCL-2637-02 LM phase contrast; Fig.24 UCL-2649-07 SEM, poor preservation, but species identifiable. Shell/Esso North Sea well number 49/10-1, depth 2850'. Early Eocene. X2,230.

# PLATE B



## PLATE C : SAME SPECIMEN TECHNIQUE

LM = Light microscope    SEM = Scanning electron microscope

1,5 & 9 Pontosphaera exilis (Bramlette and Sullivan) Romein : Fig.1 UCL-2643-10 LM crossed-nicols; Fig.5 UCL-2643-11 LM phase contrast; Fig.9 UCL-2650-01 SEM, proximal view of a poorly preserved specimen. Shell/Esso North Sea well number 49/10-1, depth 2850'. Early Eocene. X4,450.

2,6 & 10 Lanternithus minutus Stradner : Fig.2 UCL-2643-29 LM crossed-nicols; Fig.6 UCL-2643-30 LM phase contrast; Fig.10 UCL-2650-08 SEM, poor preservation. Shell/Esso North Sea well number 49/10-1, depth 2850'. Early Eocene. X4,450.

3,7 & 11 Discoaster kuepperi Stradner : Fig.3 UCL-2643-23 LM crossed-nicols; Fig.7 UCL-2643-24 LM phase contrast; Fig.11 UCL-2650-04 SEM, extremely overgrown. Shell/Esso North Sea well number 49/10-1, depth 2850'. Early Eocene. X1,560.

4,8 & 12 Chiasmolithus oamaruensis (Deflandre) Hay, Mohler and Wade : Fig.4 UCL-2637B-01 LM crossed-nicols: Fig.8 UCL-2637B-02 LM phase contrast; Fig.12 UCL-2649-16 SEM, Completely overgrown. Shell/Esso North Sea well number 49/10-1, depth 1700'. Late Eocene. X2,230.

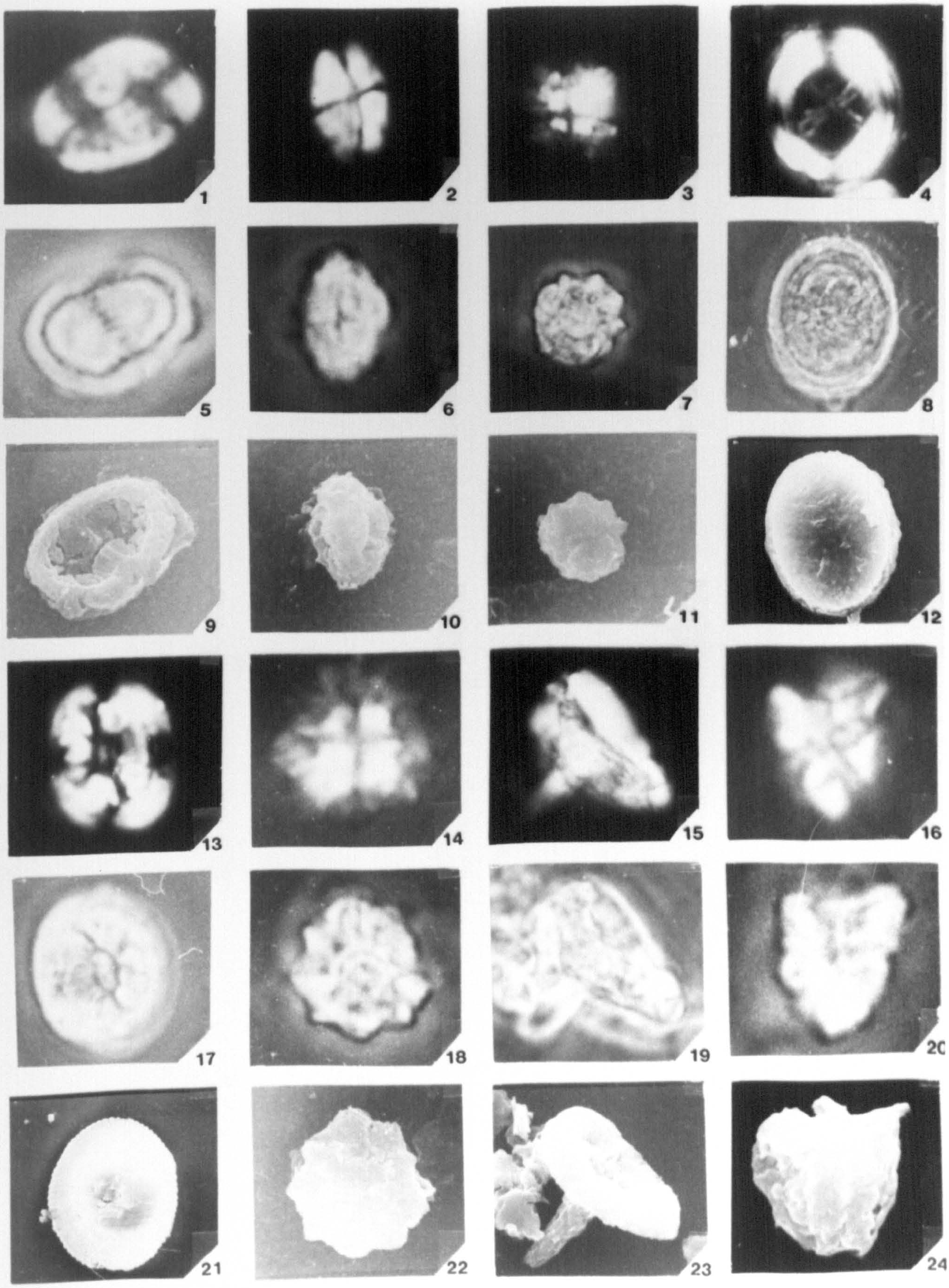
13,17 & 21 Reticulofenestra scissura Hay, Mohler and Wade : Fig.13 UCL-2637B-03 LM crossed-nicols; Fig.17 UCL-2637B-04 LM phase contrast; Fig.21 UCL-2649-20 SEM, central area overgrown. Shell/Esso North Sea well number 49/10-1, depth 1700'. Middle Eocene. X3,350.

14,18 & 22 Discoaster kuepperi Stradner : Fig.14 UCL-2643-25 LM crossed-nicols; Fig.18 UCL-2643-26 LM phase contrast; Fig.22 UCL-2650-07 SEM, very poor preservation. Shell/Esso North Sea well number 49/10-1, depth 2400'. Early Eocene. X6,700.

15,19 & 23 Placozygus sigmoides (Bramlette and Sullivan) Romein : Fig.15 UCL-2648-05 LM crossed-nicols; Fig.19 UCL-2648-06 LM phase contrast; Fig.23 UCL-2658-12 SEM, oblique proximal view. Shell/Esso North Sea well number 30/6-2, depth 9700'. Early Palaeocene. X3,350.

16,20 & 24 Sphenolithus moriformis (Brönniman and Stradner) Bramlette and Wilcoxon : Fig.16 UCL-2643-07 LM crossed-nicols; Fig.20 UCL-2643-08 LM phase contrast; Fig.24 UCL-2649-33 SEM, overgrown specimen. Shell/Esso North Sea well number 49/10-1, depth 2400'. Middle Eocene. X8,900.

# PLATE C



## PLATE D : SAME SPECIMEN TECHNIQUE

LM = Light microscope SEM = Scanning electron microscope

1 & 2 Rhabdosphaera gladius Locker : Fig.1 UCL-2601-26 SEM, side view of a specimen with a damaged base; Fig.2 UCL-2585-01 LM phase contrast, distinctive stem, but less clear basal area. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene. X4,450.

3 & 4 Chiasmolithus grandis (Bramlette and Riedel) Radomski : Fig.3 UCL-2601-10 SEM, distal view, extremely well preserved detail of teeth projecting from the inner margin of the rim, and of the central area grill; Fig.4 UCL-2585-17 LM phase contrast, slightly broken rim, but good central area cross. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene. X3,350.

5 & 6 Discoaster variablis Martini and Bramlette : Fig.5 UCL-2578-30 SEM, full specimen, quite well preserved; Fig.6 UCL-2577-26 LM phase contrast. 9099. Dtrymou, Cyprus. Pliocene. X3,350.

7 & 8 Pemma sp. : Fig.7 UCL-2601-20 SEM, very poorly preserved specimen, central area shows prominent cross structure; Fig.8 UCL-2585-12 LM phase contrast, etched rim, but segment pores visible. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene. X3,350.

9 & 10 Coccolithus pelagicus (Wallich) Schiller : Fig.9 UCL-2462-01 SEM, well preserved full coccosphere; Fig.10 UCL-2446-33 LM phase contrast. Shell/Esso North Sea well number 49/9-1, depth 1737'. Middle Eocene. X3,350.

11 & 12 Clathrolithus spinosus Martini : Fig.11 UCL-2601-11 SEM; Fig.12 UCL-2585-16 phase contrast. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene. X4,450.

13 & 14 Ericsonia fenestrata (Deflandre and Fert) Stradner in Stradner and Edwards : Fig.11b UCL-2601-13 SEM, distal view, slightly overgrown, but pores in central area grill distinct; Fig.14 UCL-2585-13 LM phase contrast, central area grill barely discernible. Shell/Esso well number 49/9-1, depth 2026'. Middle Eocene. X4,450.

15 & 16 Micrantholithus aequalis Sullivan : Fig.15 UCL-2601-31 SEM, corroded specimen, sutures barely visible; Fig.16 UCL-2585-07 LM phase contrast, sutures clearly seen. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene. X2,230.

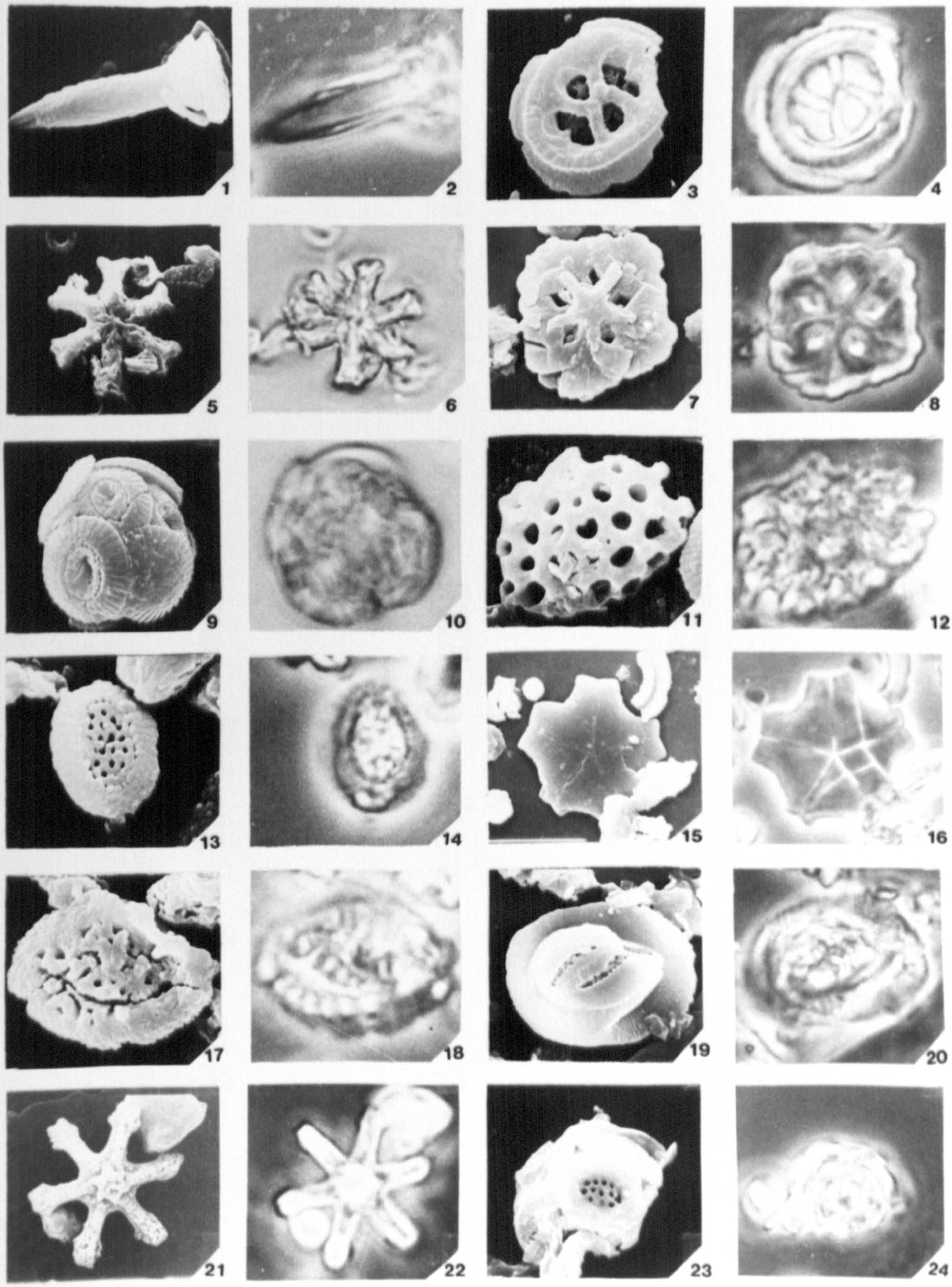
17 & 18 Helicosphaera dinesenii Perch-Nielsen : Fig.17 UCL-2601-23 SEM, distal view, coarsely reticulate central area well preserved; Fig.18 UCL-2585-08 LM phase contrast. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene. X4,450.

19 & 20 Helicosphaera dinesenii Perch-Nielsen : Fig.19 UCL-2601-09 SEM, proximal view of a well preserved specimen; Fig.20 UCL-2585-19 LM phase contrast, direction of view (proximal) discernible by flange suture being visible in bottom right hand corner of specimen. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene. X3,350.

21 & 22 Discoaster tanii Bramlette and Riedel : Fig.21 UCL-2423-15 SEM, etched specimen, termination of arms obscured; Fig.22 UCL-2392-20 LM phase contrast. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X3,350,

23 & 24 Ericsonia subdisticha (Roth and Hay) Roth : Fig.23 UCL-2658-06 SEM, broken coccosphere; Fig.24 UCL-2644-26 LM phase contrast. Shell/Esso North Sea well number 49/10-1, depth 2400'. Middle Eocene. X4,450.

# PLATE D



# WELL MATERIAL

RECOVERY AND INTERPRETATION

INCLUDING CONSIDERATION OF FORMINIFERA DATA

## 2.1 RECOVERY AND INTERPRETATION OF CALCAREOUS NANNOFOSSILS FROM WELL MATERIAL AND CONSIDERATION OF FORAMINIFERAL DATA :

The calcareous nannofossil assemblages recovered from each of the wells studied are outlined and discussed below. Full details of the lithology, wireline logs and microfossil distributions in individual wells are given in Appendix 1. Each well is divided into sections characterised by a particular combination of calcareous nannofossils, foraminifera, wireline logs and lithology. All information regarding lithology and wireline logs is derived from the completion log for that well, and foraminiferal distribution data were supplied by G.K. Gillmore (pers. comm.).

As drilling proceeds from 'top' to 'bottom', and all well material studied consisted of >50% DC in each well, it was considered expedient to discuss these wells from the highest (younger) to the lowest (older) interval, and to use "first downhole occurrences" wherever possible for accurate age assignment.

FDO = First downhole occurrence. LDO = Last downhole occurrence.

**2.1.1 WELL NUMBER 29/10-1** (See Fig.22) : 104 SWS and 100 DC samples were analysed from this central North Sea Basin well. As it was the first well studied it was extensively and intensively sampled. See Appendix 1 for sample levels.

**0000' - 1399'** **NOT SAMPLED**

**1400' - 1440'** **PLEISTOCENE**

In the highest samples recovered from this well (silts) a number of foraminifera were used to date the interval as Pleistocene (Nonion compressum, Ammonia beccarii and Elphidium incertum).

KEY TO FIGURES 22 - 31 :

A = Completion Log Information

B = Interpretation from this study

CRET. = Cretaceous

PAL. = Palaeocene

EOC. = Eocene

OL./OLIG. = Oligocene

MIO. = Miocene

PL./PLIO. = Pliocene

DAN. = Danian

E = Early    M = Middle    L = Late

? = of indeterminate or questionable age

TC = Top Chalk Formation

CGCF = Central Graben Clay Fmn

TF = Thulean Formation

EK = Ekofisk Formation

M = Maureen Formation

LA = Lista Formation

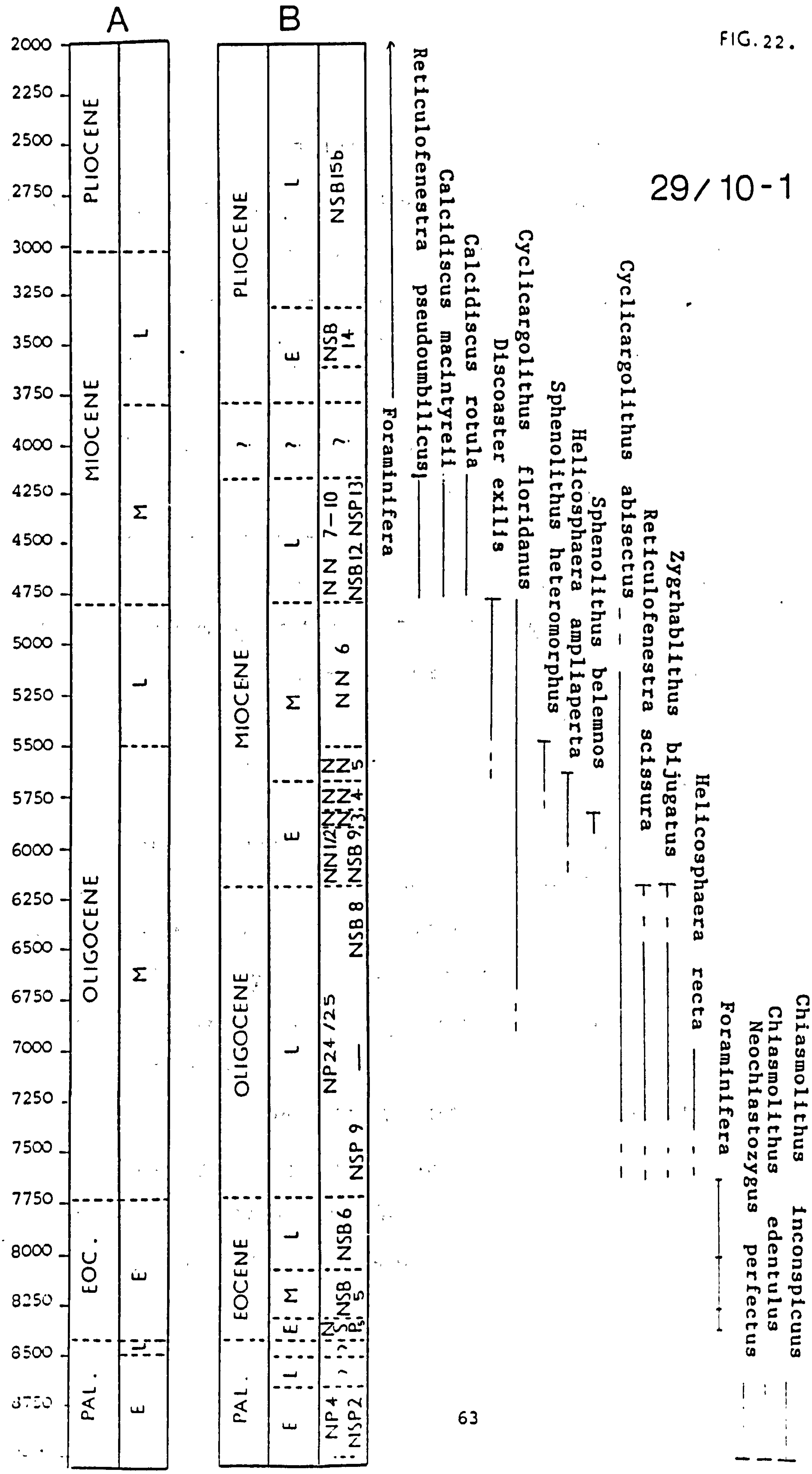
S/B = Sele and Balder Formations

NP and NN = Zones of Martini (1971) for calcareous nannofossils

NSB and NSP = Zones of King (1983) for Foraminifera

Ranges of marker species are given on the right hand side of each figure.

FIG. 22.


29/10-1
A
B
2000
2250
2500
2750
3000
3250
3500
3750
4000
4250
4500
4750
5000
5250
5500
5750
6000
6250
6500
6750
7000
7250
7500
7750
8000
8250
8500
PLIOCENE
MIOCENE
OLIGOCENE
EOC.
PAL.
EOCENE
NSB15b
NSB 14
NN 7-10
NSB12 NSP13
NN 6
NN 5
NN 3, 4
NN1/2
NSB 9
NSB 8
NP24/25
NSP 9
NSB 6
NSB 5
NP4
NSP2
Foraminifera
Reticulofenestra pseudoumbilicus
Calcidiscus macintyrei
Calcidiscus rotula
Discoaster exilis
Cyclicargolithus floridanus
Sphenolithus heteromorphus
Helicosphaera ampliaperta
Sphenolithus belemnos
Cyclicargolithus abisectus
Reticulofenestra scissura
Zygrhablithus bijugatus
Helicosphaera recta
Foraminifera
Neochiastozygus perfectus
Chiasmolithus edentulus
Chiasmolithus inconspicuus

**1441' - 1970' UNDATED**

This clay interval was not analysed for calcareous nannofossils and did not yield any age diagnostic foraminifera.

**1971' - 3800' PLIOCENE**

The FDO of the foraminifera Cibicides grossus, in association with, Cassidulina laevigata was used to date this interval as equivalent to the NSB15b zone of King (1983). No calcareous nannofossil assemblages were recovered from this extensive claystone sequence, but the foraminiferal assemblage was added to downhole by the FDO of Uvigerina venusta deurensis, which was used to mark the boundary between the Early and Late Pliocene, at 3360'. At 3500' the LDO of Cibicides grossus and the FDO of Monspielensina pseudotepida were used to mark the incoming of King's NSB14 zone.

**3801' - 4199' NO SAMPLES**

**4200' - 4800' LATE MIOCENE**

The first useful calcareous nannofossil assemblages were recovered from this interval. Although they contained few of the species used by Martini (1971) or Okada and Bukry (1980) to zone the Late Miocene, they did yield an association of Helicosphaera sellii, Calcidiscus macintyrei, Calcidiscus rotula, Sphenolithus abies, Reticulofenestra pseudoumbilicus and Helicosphaera orientalis above the FDO of Cyclicargolithus floridanus, which were used to date the interval as equivalent to Martini's (1971) NN7/11 zones.

The basal part of this section (4740' - 4800') was dated as early Late Miocene based on the FDO of the foraminifera species Bolboforma clodiusi, Siphonina reticulata and Siphonina compressa (NSP13 and NSB12 zones of King, 1983).

**4801' - 5530'** **MIDDLE MIOCENE**

Directly below the Styrian unconformity (as marked on the Completion Log, see Fig.22) the most diagnostic foraminifera from the arenaceous assemblage recovered from this interval was Reticulophragmium placenta which has a sporadic occurrence throughout the Miocene. The calcareous nannofossil assemblage included the FDO of Discoaster exilis, which could be used to indicate the incoming of the equivalent of the NN6 zone (Martini, 1971). The foraminiferal assemblage as a whole suggested the presence of the NSP12 and NSP11 zones of King (1983) which would match exactly the age suggested by the calcareous nannofossil assemblage.

**5531' - 5610'** **MIDDLE MIOCENE**

This interval included the FDO of the calcareous nannofossil Sphenolithus heteromorphus which could be used to indicate the presence of the equivalent to the NN5 zone of Martini (1971).

**5611' - 5790'** **EARLY MIOCENE**

There were no diagnostic foraminifera to be found in this interval, but the FDO of Helicosphaera ampliaperta in the calcareous nannofossil assemblage can be used to accurately locate the NN4 zone of Martini (1971) within the monotonous claystone sequence in this well.

Although Martini (1971) used many mid- and high-latitude sites to establish the 'standard' calcareous nannofossil zonation scheme, it is not often that sites with such a high latitude as the North Sea Basin are seen to yield assemblages which so closely match those proposed by Martini (1971) (see Martini and Müller, 1973 and Muller, 1979). The interval between 4801' - 5790' in this well contained all the zonal boundary species indicated for the zones NN6 - NN3, or their alternatives as proposed by Okada and Bukry (1980). This augured well for the proposal of a biozonation scheme for the Tertiary of the North Sea Basin based on calcareous nannofossils.

**5791' - 5880'** **EARLY MIOCENE**

The CN2 zone of Okada and Bukry (1980), approximating to the NN3 zone of Martini (1971), can be recognised between the FDO and LDO of Sphenolithus belemnos within this interval of the well. The N5/6 zone of Blow (1969) was suggested by the FDO of Globigerina ciperoensis, and Globigerina angulisuturalis here.

**5881' - 6180'** **EARLY MIOCENE**

The calcareous nannofossil assemblage loses definition with respect to zonation at this level in the well. Only the long-ranging Helicosphaera carteri and Helicosphaera ampliaperta appeared consistently. The NSB9 zone of King (1983) is suggested by the FDO of the foraminifera species Plectofrondicularia seminuda and Repmanina charoides, the latter of which is indicative of depths greater than 200m.

**6181' - 6999'** **LATE OLIGOCENE**

This enormous interval of claystone with only occasional limestone and marl streaks was dated as equivalent to the NP24/25 zones of Martini (1971) by the association of Cyclicargolithus abisectus (acme), Reticulofenestra scissura, Zygrhablithus bijugatus, Chiasmolithus altus, and (in the lower part) Helicosphaera recta. The FDO of the foraminifera species Marsonella communis marked the incoming of King's (1983) NSB8 zone. In general the foraminiferal assemblage consisted of agglutinated Rhabdammina. At 6700' the foraminiferal assemblage was supplemented by Turrilina alsatica, and Globigerina praescitula.

**7000' - 7744'** **EARLY OLIGOCENE ?**

At 7000' Spirosigmoidinella compressa became abundant (>15% of all forms present). Also at around 7000' some calcareous nannofossil forms more commonly associated with the Late Eocene and Early Oligocene had their FDO (i.e. Reticulofenestra umbilicus, Ericsonia formosa and Ericsonia subdisticha). It is possible that this lower part of the interval was of an older age or that it contained these forms as part of a re-worked suite from the Early Oligocene/Late Eocene interval below or from an interval cut out by the Pyrrenean unconformity (see Fig.22). Hence, although not necessarily present in the sediment pile, the former presence of Early Oligocene of the North Sea Basin may be indicated by the FDO of these species.

**7745' - 8100'** **LATE EOCENE**

Below the Pyrrenean unconformity the microfossil assemblage took a completely different form. The lithology ranged from clay to a reddish brown shale and was completely barren of calcareous nannofossils. The foraminifera present indicated an early Late Eocene age (NSB6 zone of King, 1983) based on the FDO of Reticulophragmium amplectens.

**8101' - 8360'** **MIDDLE EOCENE**

The reddish brown shale in this interval contained the FDO of the foraminifera Karreriella conversa and indicated the NSB5 zone of King (1983). No calcareous nannofossil species were found.

**8361' - 8400'** **EARLY EOCENE**

This section of the well included the marl/shale and volcanic ash sediments of the Balder Formation, represented by its distinctive Gamma ray log response on the Completion Log. The NSP5 zone of King (1983) and Sequence 10 of Stewart

(1987) (corresponding to the earliest Thanetian) could be determined by the presence of the foraminifera Globigerina gr. linaperta.

**8401' - 8700' LATE PALAEOCENE**

The foraminifera Karreriella horrida, Cystammina sp. (acme) and Spiroplectammina spectabilis were used to date this relatively poorly microfossiliferous interval of sediment.

**8701'- 9110' EARLY PALAEOCENE**

The Maureen Formation was present in this, the lowest part of the well, recognisable by its bands of coarse agglomerate containing boulders of re-worked chalks interbedded with sands and silts. The calcareous nannofossil assemblage for this interval was made up of the marker species for the upper Chiasmolithus inconspicuus Zone of Van Heck and Prins (1987), equivalent to the top of Martini's (1971) NP4 zone and the lower part of the S1 zone of Perch-Nielsen (1979). The important species being, Neochiastozygus perfectus, Chiasmolithus edentulus and Chiasmolithus inconspicuus. Foraminifera species in this interval were indicative of the NSB1b zone of King (1983) (based on Globanomalina pseudobulloides, Rzhakina minima and Globoconusa daubjergensis) and complemented the calcareous nannofossil data. Analysis of other North Sea Basin wells has shown that a 'consistent' assemblage of calcareous nannofossils over such a relatively long interval in the Early Palaeocene is unusual. It is quite possible, given the nature of the Maureen Formation, that only the lower 45' of sediment (9065' - 9110') has in situ calcareous nannofossil assemblages, the assemblages above (up to 8432') perhaps representing re-working of Danian chalk into the Maureen Formation.

2.1.2 **WELL NUMBER 21/11-1** (See Fig.23) : 37 SWS and 114 DC samples were analysed from this central North Sea Basin well at regular and frequent (rarely more than 50' between samples) intervals. See Appendix 1 for lithology and sample levels. As the majority of samples used in the investigation of this well were DC it was important to appreciate the potential for caving and to allow for its possible presence when considering the biostratigraphy of the section. Where practical only the FDO of a species (as opposed to the FOD and LDO) was used to demarcate boundaries. However, this was not always feasible and a wider consideration of the assemblage and of the relative abundances and associations of certain forms was made.

**0000' - 0939'** **NO SAMPLES**

**0940' - 1482'** **PLEISTOCENE**

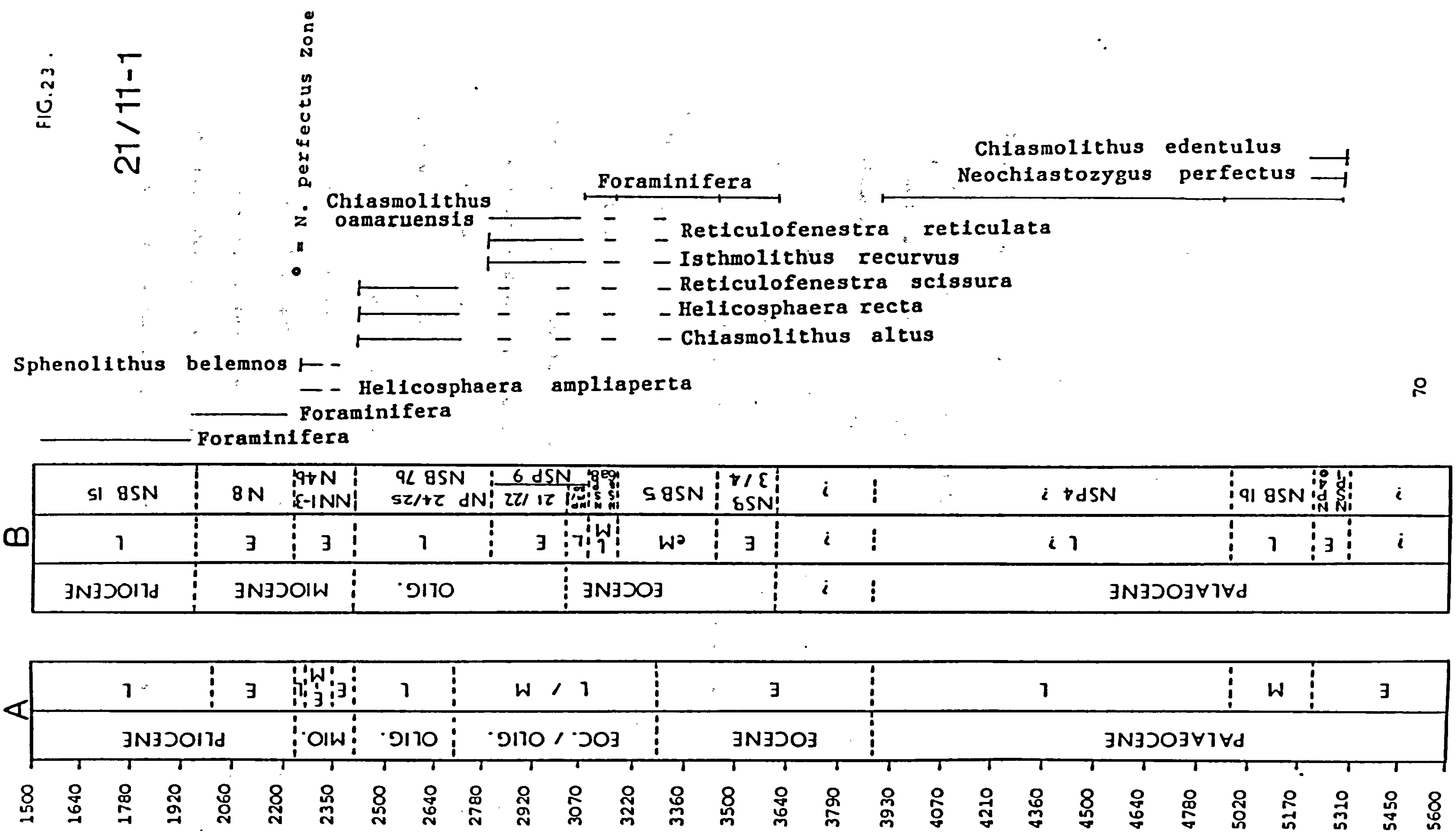
This interval consisted largely of unconsolidated sands and clays with many shell fragments. The benthic foraminifera included Cassidulina laevigata , Nonion species and Elphidium species, thus possibly indicating a shallow water environment. It was not surprising, therefore, that there was a complete lack of calcareous nannofossil and planktonic foraminifera assemblages as these forms tend to be absent from nearshore and high energy environment deposits.

**1483' - 1940'** **LATE PLIOCENE**

The FDO of the foraminifera Cibicides grossus was used to define the top of this section which was otherwise very similar to the overlying one in terms of lithology and benthic foraminiferal assemblage (Nonion species and Elphidium species again present).

FIG.23.

21/11-1



• = N. perfectus Zone
Chiasmolithus edentulus
Neochiastozygus perfectus
Foraminifera
Chiasmolithus oamaruensis
Reticulofenestra reticulata
Isthmolithus recurvus
Reticulofenestra scissura
Helicosphaera recta
Chiasmolithus altus
Sphenolithus belemnos
Helicosphaera ampliaperta
Foraminifera
Foraminifera
B
NSB 15
N8
NN1-3
N4b
NP 24/25
NSB 7b
21 /22
NSP 9
NSB 5
NSP 3/4
?
NSP4 ?
NSB 1b
L
E
eM
L ?
PLIOCENE
MIOCENE
OLIG.
EOCENE
PALAEOCENE
A
L
E
M
L / M
PLIOCENE
MIO.
OLIG.
EOC. / OLIG.
EOCENE
PALAEOCENE
1500
1640
1780
1920
2060
2200
2350
2500
2640
2780
2920
3070
3220
3360
3500
3640
3790
3930
4070
4210
4360
4500
4640
4780
5020
5170
5310
5450
5600

**1941' - 2247' EARLY MIOCENE**

The late part of the Early Miocene was inferred for this section based on the FDO of the foraminifera species Globorotaloides suteri, Tenuitelinata angustiumbilicata and Globigerina praebulloides occlusa; the first true planktonic assemblage in this well. The Completion Log indicated an age of Early to Late Pliocene for this section, but no marker species (e.g. Cibicides sp.6.) which would have supported such an age were found during this investigation. A poor calcareous nannofossil assemblage was recovered from between 2230' and 2250', but the few species present indicated an age no younger than Middle Miocene.

**2248' - 2390' (2430') EARLY MIOCENE**

Massive re-working was evident in both the foraminiferal and calcareous nannofossil assemblages within this interval. Eocene and Oligocene forms are abundant and well-preserved (as are the in situ specimens) in most of the samples and, therefore, make dating the section very difficult. Using SWS data wherever possible, the calcareous nannofossil assemblages appeared to divide this interval into an upper part dated as NN3 (Martini, 1971) equivalent; given the co-occurrence of Sphenolithus belemnos and Helicosphaera ampliaperta, and a lower part dated as approximately equivalent to the NN1 zone of Martini (1971) given the consistent occurrence of Helicosphaera mediterranea. The foraminiferal assemblage was dated as equivalent to King's (1983) N4b zone (= NN1 nannoplankton zone of Martini, 1971) from 2310' down to 2390'. From correlating the foraminiferal and calcareous nannofossil data it appeared that the interval was Early Miocene in age, and divided into an upper (2248' - 2270') of NN2/3 (Martini, 1971) equivalent age and a lower zone of NN1 (Martini, 1971) equivalent age (2271' - 2430'). The Miocene/Oligocene boundary can be quite accurately located at 2430' - 2450' between two major sand horizons in an interval of sediment lying between the Styrian and Pyrrenean unconformities.

**2451' - 2810' LATE OLIGOCENE**

Caving of Miocene species occurred, but the calcareous nannofossil marker species Chiasmolithus altus, Helicosphaera recta and Reticulofenestra scissura, in association with Zygrhablithus bijugatus and Cyclicargolithus abisectus make differentiation of this interval relatively clear. The FDO of the planktonic foraminifera Gyroidina soldenii mamillata at 2730' restricted the lower part of this interval to the early part of the Late Oligocene (= equivalent to NP24 of Martini, 1971). The base of the Oligocene is taken at the LDO of Spiroplectinella carinata and coincided with the level of the Pyrrenean unconformity. A certain amount of re-working from the Eocene is evident for a short interval above this unconformity.

**2811' - 3050' EARLY OLIGOCENE**

The planktonic foraminifera Globigerina eocena ranges from the Eocene into the Oligocene, but the association of the calcareous nannofossils Isthmolithus recurvus, Reticulofenestra umbilicus, Lanternithus minutus and, Ericsonia subdisticha, above the FDO of Reticulofenestra reticulata restricted the age range to Early Oligocene.

**3051' - 3089' LATE EOCENE**

The FDO of Reticulofenestra reticulata, in association with the calcareous nannofossil assemblage listed above, plus Ericsonia formosa and Chiasmolithus oamaruensis indicated the presence of a Late Eocene assemblage, equivalent in age to the NP19/20 zones of Martini (1971). The Oligocene/Eocene boundary was not clearly demarcated on the Completion Log as it lies within a monotonous unit of sediment.

**3090' - 3200' LATE MIDDLE EOCENE**

The FDO of the foraminifera Globigerapsis index was taken to indicate a Middle Eocene age and delimited the top of this zone. The calcareous nannofossil assemblage showed no change from the preceding section, and was assumed to represent caving from the higher level. The absence of marker species such as Rhabdosphaera gladius, Nannotetrina fulgens and Chiasmolithus solitus suggested that the assemblage was indeed caved.

**3201' - 3450' EARLY MIDDLE EOCENE**

Abundant assemblage of calcareous nannofossils, but they proved to again represent caving. The FDO of the planktonic foraminifera Planulina palmarae was used to mark the top of this section.

**3451' - 3630' EARLY EOCENE**

The lower part of this section is completely barren of calcareous nannofossils, but the interval from 3451' - 3500' still contained a diverse assemblage of caved specimens. The FDO of the foraminifera Turrillina brevispira and the first sporadic occurrence of the diatom Coscinodiscus sp.1. were taken to indicate the upper boundary of a zone equivalent to King's (1983) NSB3/4 zone.

**3631' - 3770' BARREN**

This interval is completely barren of foraminifera and only contained a limited assemblage of caved calcareous nannofossil forms. Although there is no distinctive Gamma ray log response indicated on the Completion log, the overall position of this interval suggested that it lies within the Balder Formation or an equivalent.

**3771' - 4859' LATE PALAEOCENE**

The only evidence for the existence of the Late Palaeocene within this section was the increased abundance of Coscinodiscus sp.1. There was a consistent occurrence of caved forms (both calcareous nannofossils and foraminifera), but no in situ specimens which would have facilitated a more accurate dating of this large interval.

**4860' - 5219' LATE PALAEOCENE**

The FDO of Spiroplectammina spectabilis in a SWS suggested the presence of a Late Palaeocene assemblage, however, there was little other foraminiferal evidence to support this age assignment, and a complete lack of calcareous nannofossils.

**5220' - 5310' EARLY PALAEOCENE**

Diverse and abundant calcareous nannofossil and foraminiferal assemblages appeared below the unconformity at 5220'. These provided an accurate and reliable date for the interval. Using the zonation schemes of Perch-Nielsen (1979) and Van Heck and Prins (1987) it was possible to divide the Early Palaeocene of the North Sea Basin much more finely than with the schemes of either Romein (1979) or Martini (1971). The abundant presence of large specimens of Neochiastozygus perfectus in association with a high percentage of Chiasmolithus edentulus (in relation to other species of Chiasmolithus and Cruciplacolithus) clearly indicated the presence of the N. perfectus Zone (Van Heck and Prins, 1987) which is correlated with the top of the Early Palaeocene (equivalent to the top of Martini's (1971) NP4 zone) and with the top of

'Danian' sedimentation. This zone also included the FDO (abundant) of large Towelus species, such as Towelus tovae and Towelus eminens.

**5311' - 5490' BARREN**

Samples analysed from this Danian chalk (Ekofisk Formation) were either completely barren, or contained only specimens which had been re-worked from the Cretaceous intervals below (presumably during the Laramide tectonic phase).

**2.1.3 WELL NUMBER 21/30-1 (See Fig.24) :** 81 SWS and 14 DC samples were analysed from this central North Sea Basin well. These were approximately equally spaced throughout the 6698' of Tertiary sediment in the well (see Appendix 1 for sample levels).

**0000' - 2000' NO SAMPLES**

Poorly consolidated clay and sand with shell fragments, of Pleistocene age according to the Completion Log.

**2001' - 3550' BARREN**

This extensive interval of greenish-grey to dark grey claystone (above the Late Alpine, ?Attican, and Styrian unconformities) contained a high number of SWS, but all of them proved to be barren of calcareous nannofossils. No investigation was carried out for foraminifera in this interval, thus the Pliocene - Middle Miocene age suggested by the Completion Log cannot be confirmed.

**3551' - 4088' MIDDLE/LATE MIOCENE**

This section, also bounded by unconformities, contained a relatively poor calcareous nannofossil assemblage. The only consistent member of the assemblage with any biostratigraphical significance was Reticulofenestra pseudoumbilicus,

FIG. 24.

21/30-1

• = upper C. inconspicuus Zone

which has its LDO in the late Middle Miocene in the North Sea Basin. Other species, more normally associated with the Late Miocene/Pliocene, such as Helicosphaera sellii, occurred at the level of the upper (Alpine, ?Attican) unconformity (see Fig.24).

**4089' - 4369' EARLY MIOCENE**

The calcareous nannofossil assemblages recovered from this level appear to satisfy the criteria for the recognition of the equivalent to Martini's (1971) NN3 and NN4 zones. The FDO's of both Sphenolithus belemnos and Helicosphaera ampliaperta are clear. Sphenolithus heteromorphus occurred near to the top of this interval and Cyclicargolithus floridanus and Helicosphaera euphratis became extinct toward the upper boundary. The co-extinction (FDO) of H. ampliaperta, S. heteromorphus and C. floridanus would appear to indicate that the time interval equivalent to Martini's (1971) NN5 and NN6 zones is absent from this well.

**4370' - 4474' EARLY MIOCENE**

A narrow interval of time can be differentiated by the total range of S. belemnos. The CN2 zone of Okada and Bukry (1980), approximately equivalent to the NN3 zone of Martini (1971), is represented.

**4475' - 4486' EARLY MIOCENE**

Although none of the traditional marker species for Martini's (1971) NN2 zone were found in this interval, nor any of the markers for accepted equivalent zones (i.e CN1c zone of Okada and Bukry, 1980) it is proposed that the interval between the LDO of H. ampliaperta and the LDO of S. belemnos may be used as an alternative in the North Sea Basin (see Chapter 5 for discussion).

**4487' - 4600'?** **EARLY MIOCENE**

A very poor assemblage, consisting of a few long-ranging Miocene species, was recovered from this section. Tentative Early Miocene age.

**4601'? - 5201'** **BARREN**

On the evidence of the calcareous nannofossil assemblages from above and below this interval the Miocene/Oligocene boundary should occur somewhere within this section. Unfortunately it was completely barren of calcareous nannofossils and no investigation of foraminifera was undertaken, hence the boundary cannot be determined biostratigraphically. The wireline logs show only one major deflection, but this occurred at a casing point where such deviations are to be expected. The lithology is quite uniform claystone with minor limestone streaks near the base, lacking unconformities or any other obvious structural breaks. It is possible that the boundary is near to the dolomite streaks (minor wire line log response) between 4500' and 4550', with the sparse Early Miocene assemblage recovered from the DC sample at 4600' representing caving from a little way above. the position of these dolomite streaks coincides with the top arenaceous fauna according to the Completion Log.

**5202' - 5420'** **LATE OLIGOCENE**

The quality of the calcareous nannofossil assemblages recovered from within this interval varied considerably. On the whole it was sufficient to indicate a Late Oligocene age based on the association of Cyclicargolithus abisectus, Reticulofenestra scissura and Chiasmolithus altus (equivalent to the NP24/25 zones of Martini, 1971).

**5421' - 6051'** **EARLY OLIGOCENE**

A number of SWS near to the top of this interval contained calcareous nannofossil assemblages broadly similar to those in the interval above. However, the assemblages here were much sparser and poorly preserved in comparison and thus were not considered stratigraphically important. This section contained the first agglutinated foraminiferal assemblages studied in this well. They provided a distinctive Early Oligocene age based on the association of Ammodiscus latus, Spirosigmoidinella compressa and Trochammina quadriloba - equivalent to King's (1983) NSB 7/8 zone. There is little faunal change through this section down to the level of the Pyrrenean unconformity (see Fig.24).

**6052' - 6110'** **MIDDLE EOCENE**

Below the level of the unconformity there is a distinct change in the composition of the foraminiferal assemblage, with the FDO of Karriella conversa indicative of a Middle Eocene age. No calcareous nannofossils were recovered from this interval.

**6111' - 6210'** **MIDDLE EOCENE**

The FDO of Bolivinopsis spectabilis (form A) was used to define the top of the equivalent to the NSB5 zone of King (1983) which corresponded to a major deflection in the sonic log. The foraminifera present belong to a Rhabdammina biofacies, which tend to be common in the centre of the North Sea Basin, and contained agglutinating foraminifera. This particular biofacies is most widespread in the Late Palaeocene and Eocene and, although the bathymetry is uncertain, it is thought to be indicative of relatively deep water.

**6211' - 6383' EARLY EOCENE**

As with the whole of the rest of the Eocene section in this well, this particular interval was barren of calcareous nannofossils. However, the foraminiferal assemblage continued to improve downhole and the FDO of Ammomarginulina macrospira and Bolivinopsis navarroanus was used to define the top of a zone equivalent to the NSB4 zone of King (1983).

**6384' - 6477' EARLY EOCENE**

The distinctive Balder Formation was well defined by the Gamma ray log response in this interval. In terms of microfossils the FDO of Coscinodiscus sp.1 was used to define the top of King's (1983) NSP4 zone, in the absence of foraminifera and calcareous nannofossils.

**6478' - 6689' LATE PALAEOCENE ?**

This interval is completely barren with respect to calcareous nannofossils (as in all other well material) and contained only a poor foraminiferal assemblage which indicated an age equivalent to King's (1983) NSB2 zone.

**6690' - 6850' EARLY PALAEOCENE**

Few of the marker species (calcareous nannofossils) used by Martini (1971) or Okada and Bukry (1980) occurred with any consistency in this part of the well, so it is not surprising that their 'standard' zonation schemes are not applicable. However, the species used by Perch-Nielsen (1979) and Van Heck and Prins (1987) for the type Danian in Denmark, and the North Sea Basin respectively, did occur in reasonable numbers and can be applied. The association of Neochiastozygus perfectus, Chiasmolithus edentulus and Chiasmolithus inconspicuus throughout this interval indicated the presence of the upper Chiasmolithus inconspicuus Zone of Van Heck and Prins (1987) which is approximately equivalent to the top of Martini's (1971) NP4 zone.

The foraminifera from this part of the well also provide a good assemblage in terms of biostratigraphy. The NSP1b and NSB1b zones of King (1983) are recognised on the association of Bolivinopsis spectabilis, Globorotalia compressa, Trochammina ruthvenmurrayi and Globoconusa daubjergensis. The latter of these species is thought to occur higher than was indicated by King (1983), thus giving an age which agrees exactly with that indicated by the calcareous nannofossils.

**2.1.4 WEll NUMBER 49/9-1** (See Fig.25) : 25 SWS and 8 DC samples were analysed from this southern North Sea Basin well. The samples were taken at regular and frequent intervals throughout this mainly Eocene section of monotonous claystone with a basal limestone. See Appendix 1 for lithological log and sample levels.

**0000' - 1287'** **NO SAMPLES**

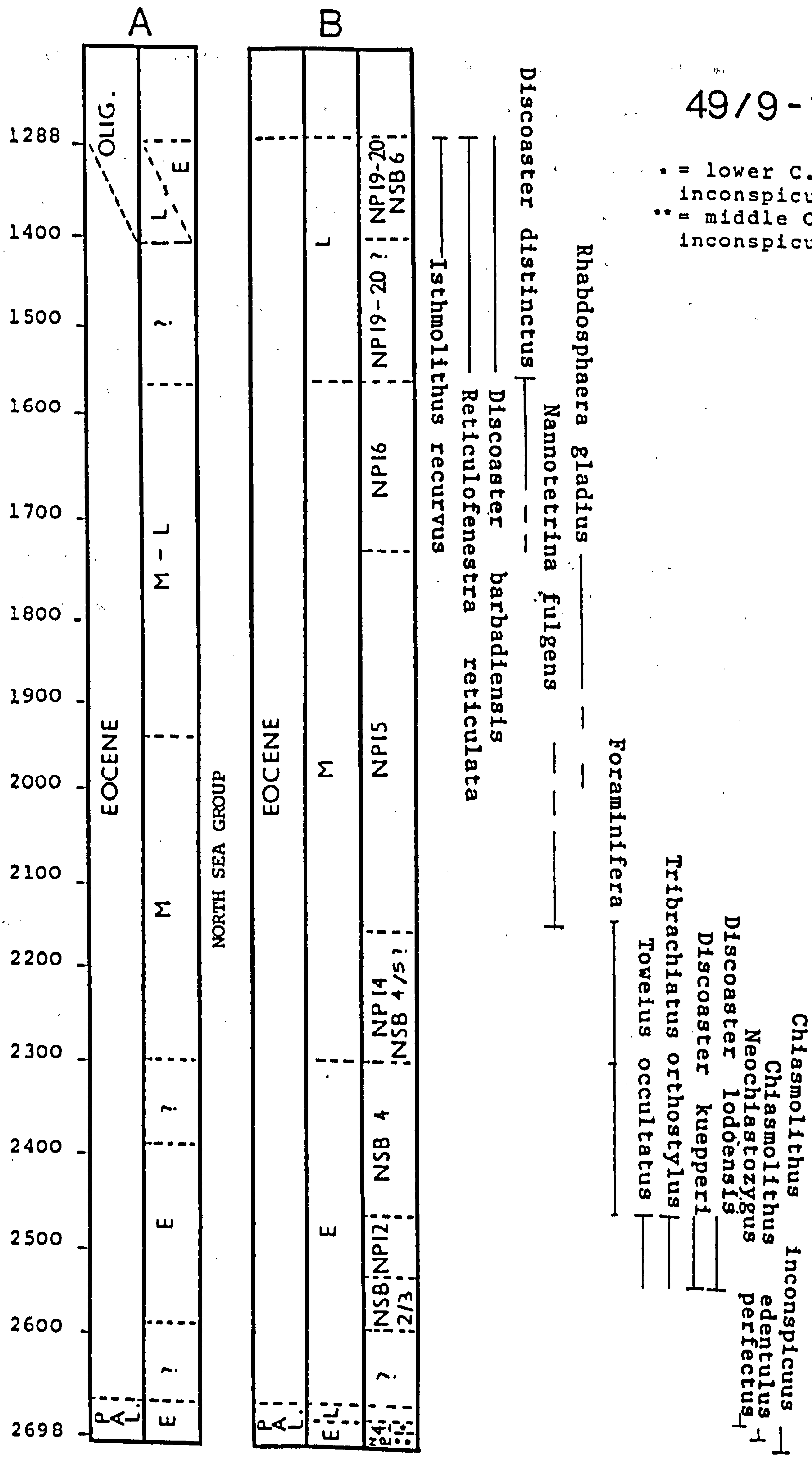
**1288' - 1389'** **LATE EOCENE**

The upper part of this well contained a useful assemblage of benthic foraminifera, including one of the marker species (Bryzalina cookii) for King's (1983) NSB6 zone. The species used to sub-divide the zone into NSB6a and NSB6b (Cibicidoides granulosus) was not present in this well, but a diverse and well-preserved assemblage of calcareous nannofossils was present and could be used to assign an age of Late Eocene (equivalent to the NP19/20 zone of Martini, 1971). This interpretation was based on the co-occurrence of Reticulofenestra reticulata and Isthmolithus recurvus. The foraminifera Turrillina

FIG. 25.

49/9-1

• = lower C. inconspicuus Zone
•• = middle C. inconspicuus Zone



brevispira, a marker species for NSB4 (King, 1983) was found in a SWS at 1360', but it was rare and probably re-worked.

**1390' - 1534' LATE EOCENE**

The two DC samples within this interval contained a similar calcareous nannofossil assemblage to that of the preceding level, but included the FDO's of Sphenolithus celsus, Discoaster saipanensis and Discoaster barbadiensis. In the absence of Sphenolithus pseudoradians and Chiasmolithus oamaruensis it was likely that the equivalent of NP19/20 (Martini, 1971) zone could still be applied. The foraminiferal assemblages were impoverished and could not be used successfully to refine the biostratigraphy.

**1535' - 1736' MIDDLE EOCENE**

This section contained a very diverse and well-preserved assemblage of calcareous nannofossils which was used to date the sequence as equivalent to Martini's (1971) NP16 zone. According to Martini (1971) the top of this zone is marked by the FDO of Chiasmolithus solitus, but Aubry (1986, p.276) suggested that in the absence of this species from north-west European sections the FDO (=LOD) of Discoaster distinctus could be used instead. In this well both C. solitus and D. distinctus were present, but they had different FDO's. As Birkelundia staurion and Chiasmolithus nitidus had the same FDO as D. distinctus at 1535', and Discoaster saipanensis had its LDO, these events are more likely to mark the top of zone NP16 in this well than the FDO of C. solitus at 1650'. The occurrence of Helicosphaera compacta within this zone accords with the LDO of the species as recorded by Aubry (1983, p.94). Foraminiferal data was inconclusive over this interval; the FDO's of Percultazaneria wetherellii and Uvigerina batjeri indicated a broad Eocene age.

A disconformity was evident between this part of the section and the overlying intervals. The absence of Martini's (1971) zones NP17/18 (or equivalents) was clearly indicated by the absence of Chiasmolithus oamaruensis in this well. The lack of SWS between 1389' and 1535' meant that it was difficult to determine whether a barren interval existed here, with caving from the higher zone represented at 1440' and 1470', or whether the assemblages at 1440' and 1470' were in situ and an unconformity existed around 1500'. There was no evidence for an unconformity shown on the Completion Log, but in such a monotonous series of green/grey claystones it would have been difficult to detect using only wireline log responses.

1737' - 2167' MIDDLE EOCENE

A well-defined interval in terms of calcareous nannofossil assemblages, based upon the FDO of the distinctive Rhabdosphaera gladius and the LDO of Nannotetrina species. The assemblage agreed closely with that suggested by Martini (1971) for the NP15 zone. The foraminiferal assemblage was supplemented by the addition of Gyroidina soldenii, but still remained vague in terms of biostratigraphical application.

2168' - 2298' MIDDLE EOCENE

In the absence of Discoaster sublodoensis it was difficult to date this section accurately, however, below the LDO of Nannotetrina species the assemblage still contained Sphenolithus furcatolithoides which indicated the presence of the upper part of Martini's (1971) NP14 zone. The FDO of the foraminifera Cibicidoides allenii and Alabamina wilcoxensis indicated an age similar to that of the calcareous nannofossil assemblage, equivalent to the NSB4/5 zone of King (1983).

**2299' - 2463'** **EARLY EOCENE**

There was a lack of calcareous nannofossils in this section, but the evidence from above and below suggested that it represented the equivalent of Martini's (1971) lower NP14 and NP13 zones. Nowhere in the North Sea or neighbouring basins has this zone been represented by in situ calcareous nannofossils during the course of this study. The foraminiferal assemblage included the FDO of Cyclammina amplectens and a Rhabdammina biofacies (indication of deep water). At 2400' there was an increase in the abundance of C. amplectens and, hence a greater certainty of the presence of King's (1983) NSB4 zone or its equivalent. The age suggested by the foraminiferal assemblages confirmed that which could only be inferred by calcareous nannofossils.

**2464' - 2528'** **EARLY EOCENE**

A single DC sample between two barren SWS's contained a reasonably diverse assemblage of calcareous nannofossils which could be used to date this interval as NP12 zone (Martini, 1971) based on the association of Toweius occultatus, Discoaster kuepperi, Tribrachiatus orthostylus and Discoaster lodoensis, and Pontosphaera exilis. The presence of Pontosphaera exilis in the assemblage could be used to refine the age further to Unit IIIb or IV of Steurbaut (1988) (= earliest NP12 zone).

**2529' - (2540') 2590'** **EARLY EOCENE**

The FDO's of the foraminifera Karriella conversa and Glomospira choroides followed by the FDO of Coscinodiscus sp.1. a short distance below indicated the presence of an assemblage equivalent in age to King's (1983) NSB2/3 zone. This foraminiferal assemblage was of a broadly similar age to the calcareous nannofossil assemblage which was found directly above it (2464' - 2528'). The change from a planktonic to a benthic assemblage within such a short interval (time and distance) would appear to indicate a rapid change in environmental conditions within the deep water (as evidenced by a Rhabdammina biofacies) basin, perhaps of turbiditic origin.

**(2541') 2591' - 2650' BARREN**

This interval corresponded to the base of the Eocene section seen in all the wells investigated, and was taken to represent the southern North Sea Basin equivalent of the Balder Formation (Thulean Tuff Formation ?). The typical Gamma ray log response is seen to occur from 2540' - 2650', and it is possible that the foraminiferal assemblages recovered from between 2540' - 2590' were caved from the interval directly above.

**2651' - 2657' LATE PALAEOCENE**

Slightly above the unconformity which separated the North Sea Group from the underlying Danian limestones there was a thin veneer of early Late Palaeocene sediment which was dated on the basis of an influx of agglutinated foraminiferal species, e.g. Ammodiscus cretacea, Glomospira choroides and a Rhabdammina biofacies.

**2658' - 2680' EARLY PALAEOCENE**

Between these depths the FDO of the foraminifera Nodosaria tarsicostata in association with the calcareous nannofossil species Chiasmolithus edentulus and Chiasmolithus inconspicuus was used to accurately date this interval as late Early Palaeocene. Applying the zonation of Van Heck and Prins (1987) this interval is equivalent to the middle C. inconspicuus Zone.

**2681' - 2698'** **EARLY PALAEOCENE**

Below 2680' there was a marked decline of Chiasmolithus edentulus, therefore, this section was dated as lower C. inconspicuus Zone of Van Heck and Prins (1987).

The zonations of Perch-Nielsen (1979), Van Heck and Prins (1987) and Varol (in press) allow a much more refined sub-division of the Palaeocene of the North Sea Basin than either the zonations of Romein (1979) or Martini (1971), which used marker species which were often rare or absent from the North Sea Basin or too widely spaced temporally to be of real use.

**2.1.5 WELL NUMBER 16/8-1** (See Fig.26) : 34 SWS and 10 DC samples were analysed from this central North Sea Basin well which was located near to the northern margin of the basin. See Appendix 1 for sample levels and detailed lithology.

**0000' - 1799'** **NOT SAMPLED**

**1800' - 2309'** **BARREN**

Two ditch cuttings from this interval were found to be barren of calcareous nannofossils. The Completion Log suggested a division between the Upper Miocene and Middle/Lower Miocene at 1860', but the lack of any microfossil assemblage or any obvious change in lithology made it difficult to confirm.

**2310' - 3220'** **MIOCENE**

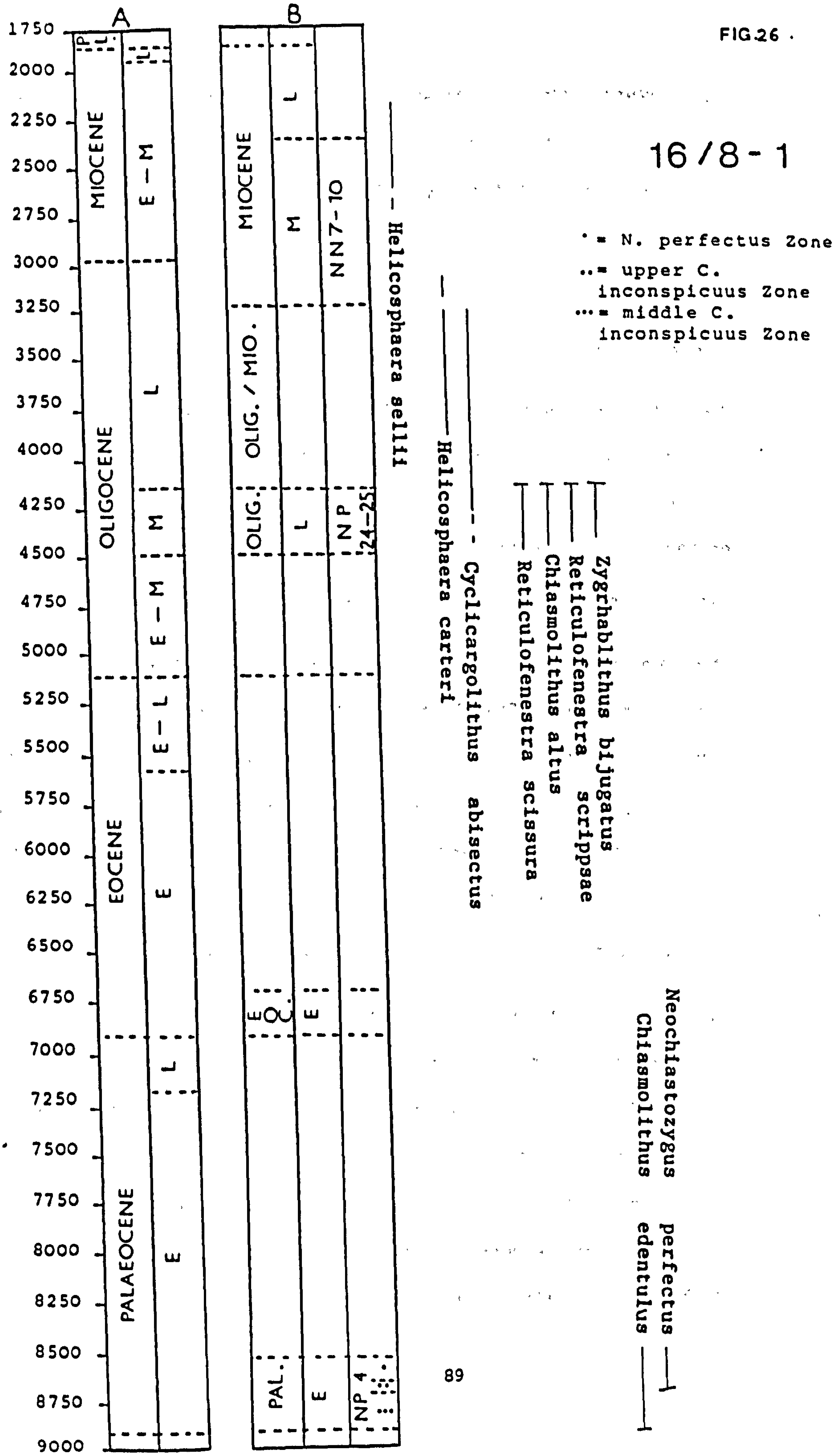
This relatively large interval was covered by only 4 samples. The one side wall sample examined (3075') contained a very poor assemblage of calcareous nannofossils which reflected the paucity of specimens at this level better than the ditch cuttings samples which had superficially more diverse assemblages. Reticulofenestra pseudoumbilicus and Helicosphaera sellii forms found at this level were probably caved specimens.

**3221' - 4140'** **MIOCENE/OLIGOCENE**

The two side wall samples at the top of this section contained assemblages recognised as typical for this boundary zone in the Central North Sea. The FDO of large Cyclicargolithus abisectus in association with Helicosphaera carteri (Miocene) and Reticulofenestra scrippsae (Oligocene) was indicative of the 'mixed' assemblage which occurred at this level. There was a noticeable increase in the Sonic Log response in the passage from Miocene to Oligocene sediment (which may have greater compaction).

FIG.26 .

16/8-1



A
B
1750
2000
2250
2500
2750
3000
3250
3500
3750
4000
4250
4500
4750
5000
5250
5500
5750
6000
6250
6500
6750
7000
7250
7500
7750
8000
8250
8500
8750
9000
P.
L.
MIOCENE
E – M
OLIGOCENE
M
E – M
E – L
EOCENE
E
PALAEOCENE
MIOCENE
M
NN7-10
OLIG. / MIO.
OLIG.
NP 24–25
PAL.
NP 4
· = N. perfectus Zone
·· = upper C. inconspicuus Zone
··· = middle C. inconspicuus Zone
Helicosphaera sellii
Helicosphaera carteri
Cyclicargolithus abisectus
Zygrhablithus bijugatus
Reticulofenestra scrippsae
Chiasmolithus altus
Reticulofenestra scissura
Neochiastozygus perfectus
Chiasmolithus edentulus

**4141' - 4500' LATE OLIGOCENE**

The first exclusively Late Oligocene assemblage occurred in this interval. The FDO's of Reticulofenestra scissura, Zygrhablithus bijugatus, Chiasmolithus altus and Sphenolithus ciperoensis(?) were excellent markers for the equivalent of Martini's (1971) NP24/25 zones.

**4501'-5090' BARREN**

The effect of the sudden influx of large sand bodies was reflected in the complete absence of any calcareous nannofossils in this interval.

**5091'- 6690' BARREN**

It is usual in this area for the Eocene interval to be barren of calcareous nannofossils. Even in the lowest part of this section where the PT22 zone is indicated there was no Early Eocene assemblage found.

**6691' - 6900' BARREN**

The Balder and Sele Formations are indicated in this section by their distinctive Gamma ray log responses and lithologies. They are known to be of the earliest Eocene age , but are completely barren of calcareous nannofossils.

**6901'-8522' BARREN**

This section was again typical for the Central North Sea in that the sands and silts of Late Palaeocene age were completely barren of calcareous nannofossils.

**8523' - 8640' EARLY PALAEOCENE**

A single side wall sample from within this interval yielded an assemblage which contained abundant Chiasmolithus edentulus and Neochiastozygus perfectus. It is unusual for N. perfectus to be present in such high numbers, but Van Heck & Prins (1987) recognised their N. perfectus Zone on the basis of its "common occurrence". It is therefore proposed that the top of the NP4 zone is present here.

**8641' - 8677' EARLY PALAEOCENE**

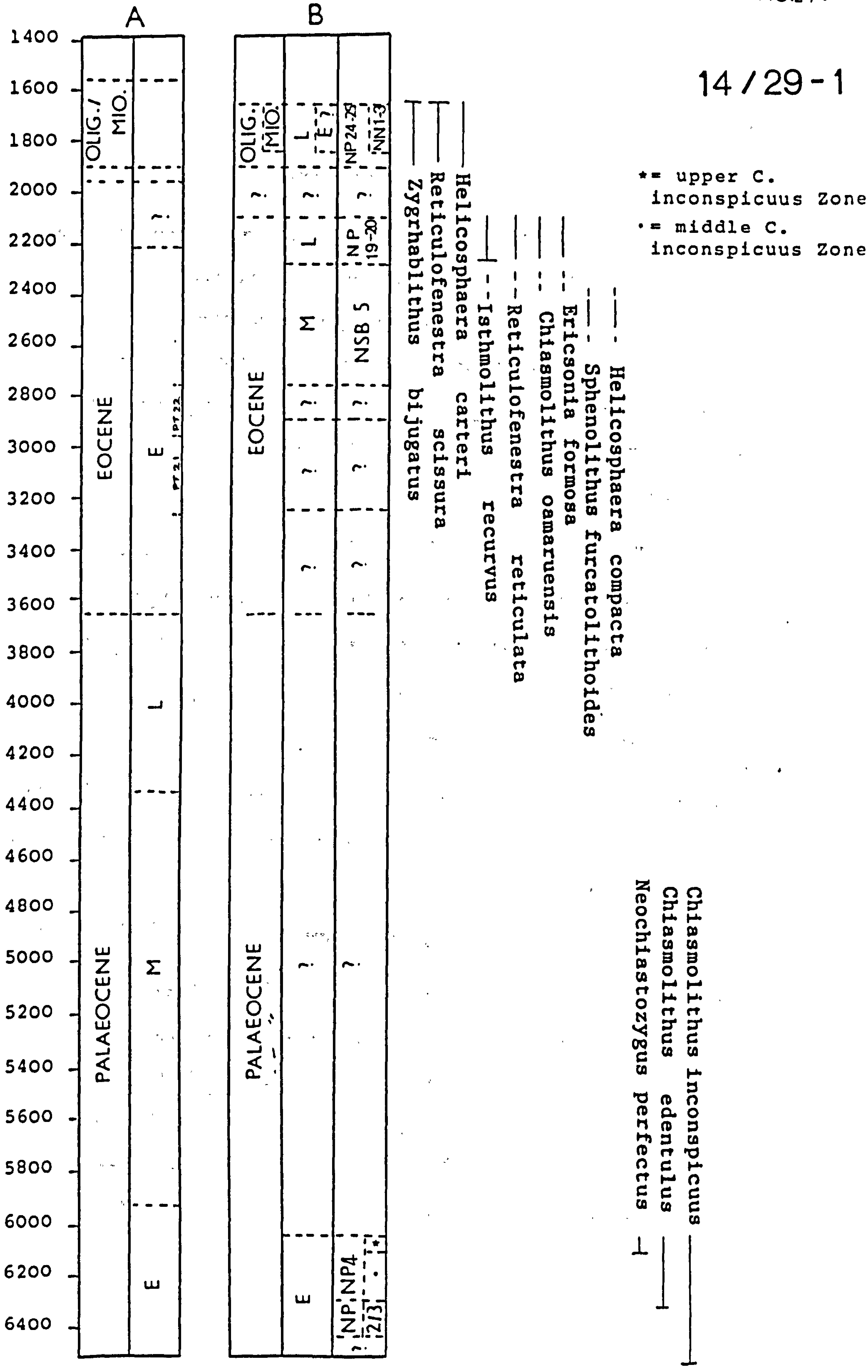
The assemblage within this interval was basically the same as that in the one above, except that there was a definite decline in the proportion of Neochiastozygus perfectus present. Van Heck & Prins (1987) indicated that the difference between the upper Chiasmolithus inconspicuus Zone and the N. perfectus Zone was the proportion of N. perfectus, it is proposed that this level is indicative of the upper C. inconspicuus Zone and thus lies conformably below the previous interval.

**8678' -8900' EARLY PALAEOCENE**

The absence of Neochiastozygus perfectus from assemblages which consistently contained Chiasmolithus edentulus was evidence that a further conformable change of zone had occurred; upper Chiasmolithus inconspicuus Zone to middle C. inconspicuus Zone, still within the equivalent of Martini's (1971) NP4 zone.

**2.1.6 WELL NUMBER 14/29-1** (See Fig.27) : 17 SWS and 18 DC samples were analysed from this central North Sea Basin well. It is situated on the western edge of the basin and, therefore, had a much shorter sediment pile than any of the other central North Sea Basin wells. The lithology was basically siltstone, sandstone with occasional coal and limestone beds (Fladen Sand Formation) and the familiar chalk of the Early Palaeocene strata. See Appendix 1 for sample levels and detailed lithology.

FIG.27.


14/29-1
A
B
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
4200
4400
4600
4800
5000
5200
5400
5600
5800
6000
6200
6400
OLIG./MIO.
EOCENE
PALAEOCENE
L
M
E
PT 21
PT 22
E ?
NP24-25
NN1-3
NP 19-20
NSB 5
NP 2/3
NP4
*= upper C. inconspicuus Zone
•= middle C. inconspicuus Zone
Helicosphaera compacta
Sphenolithus furcatolithoides
Ericsonia formosa
Chiasmolithus oamaruensis
Reticulofenestra reticulata
Isthmolithus recurvus
Helicosphaera carteri
Reticulofenestra scissura
Zygrhablithus bijugatus
Chiasmolithus inconspicuus
Chiasmolithus edentulus
Neochiastozygus perfectus

0000' - 1669' NO SAMPLES

1670' - 1810' EARLY MIOCENE ? - OLIGOCENE

The calcareous nannofossil assemblage in this interval was very poor and of little use stratigraphically. The co-occurrence of Zygrhablithus bijugatus and Reticulofenestra scissura in the lower part appeared to indicate the Late Oligocene was present, but foraminiferal data included the presence of the local FDO of Florilus boueanus, Bulimina elongata, and Plectofrondicularia seminuda which have FDO's ranging from King's (1983) NSB14 zone to NSB9 zone (Early to Late Miocene).

1811' - 1900' OLIGOCENE

The presence of the foraminifera Cassidulina caraptana and a few poorly preserved calcareous nannofossil species appeared to date this interval as Oligocene (probably Late Oligocene).

1901' - 2089' BARREN

A sandy interval in which very few samples were analysed - those which were studied proved to be barren of calcareous nannofossils and foraminifera (both planktonic and benthic).

2090' - 2220' LATE EOCENE

The calcareous nannofossil assemblage found between these depths was the first in the well which could be used with a degree of confidence. The co-occurrence of Isthmolithus recurvus and Reticulofenestra reticulata along with the presence of Chiasmolithus oamaruensis and Ericsonia formosa indicated an age equivalent to Martini's (1971) NP19/20 zone. The foraminifera in this interval were mostly caved specimens from higher levels.

**2221'- 2750' MIDDLE EOCENE**

There was a lot of caving of calcareous nannofossils evident in this interval. The assemblages were not very different from those in the interval above, but the FDO's of species such as Sphenolithus furcatolithoides and Helicosphaera compacta suggested a Middle, rather than Late, Eocene age for these samples. There was a diverse foraminiferal assemblage in this interval which also supported a Middle Eocene age (probably NSB5 zone of King, 1983). The foraminiferal assemblage included Globorotalia pentacamarata, and Planulina palmarae.

**2750' - 2870' BARREN**

Although both calcareous nannofossil and foraminiferal assemblages occurred in this interval, they were assumed to be caved. The microfossils indicated a Middle Eocene age as above, but the Completion Log indicated the presence of the PT22 (Shell/Esso notation) zone (see Fig.27). In previous wells this zone has either yielded a good Early Eocene assemblage, or has been barren. It is thought that in this well the PT22 zone was barren, with caving accounting for the assemblages present.

**2871' - 3230' BARREN**

This interval was completely barren of calcareous nannofossils (in situ or contaminants). The PT21 zone (Shell/Esso notation), which this interval represented according to the Completion Log, usually contains the very distinctive Balder Formation (ash marker) with its distinctive gamma ray log response, however, the log response in this well was remarkable for its uniformity. It is possible that in a well such as this, which has a 'shelf' location, the effects of the vulcanicity responsible for the distinctive Balder Formation were slight and, therefore, the formation was not recognisable.

**3231' - 5927' BARREN**

The lower part of the Fladen Sand Formation, the Central Graben Clay Formation and the Halibut Sand Formation (Forties Group) were represented by some 2700' of sands and silts, with occasional limestones and even coal. These proved to be totally devoid of calcareous nannofossils. The nature of the sediments suggested a deltaic environment, one which would have been too shallow and too high-energy for the preservation of calcareous nannofossils. No foraminiferal evidence was available for this interval.

**5928' - 6299' EARLY PALAEOCENE**

This interval can be dated as equivalent to Martini's (1971) NP4 zone, but the marker species Ellipsolithus macellus quoted by Martini (1971) was not present. A more refined zonation can be achieved by using the criteria of Van Heck & Prins (1987) and those of Perch-Nielsen (1979). The LDO'S of Neochiastozygus perfectus and Chiasmolithus edentulus were used to sub-divide this interval into the S1/D10 zones of Perch-Nielsen (1979) and the upper and middle Chiasmolithus inconspicuus Zones of Van Heck & Prins (1987) at 6095'. It is interesting to note that this sub-division corresponded to the change from the Halibut Sand Formation to the Top Chalk Formation, and from the Forties Group to the Chalk Group. Foraminiferal data from this interval and the one below indicated an age of NSP 1a (after King, 1983).

**6300' - 6450' EARLY PALAEOCENE**

This interval was dominated by the presence of Prinsius dimorphosus, with minor occurrences of Cruciplacolithus tenuis, Cruciplacolithus intermedius and possibly

Chiasmolithus danicus at the very top of the interval. Using the criteria of Van Heck & Prins (1987) this section can be dated as Chiasmolithus asymmetricus/lower Chiasmolithus danicus Zone, equivalent to D4/5 zone of Perch-Nielsen (1979).

This well differs from the others studied from the Central North Sea Basin in a number of ways :

1. It has a marginal position relative to the basin, and therefore has a noticeably shorter sediment sequence.

2. There is no extensive Miocene/Late Oligocene interval as in previous wells.

3. It is the only well in the Central Basin which contained Late and Middle Eocene calcareous nannofossils, and thus enabled a correlation to be made with the wells in the southern Basin which have well-developed intervals of this age.

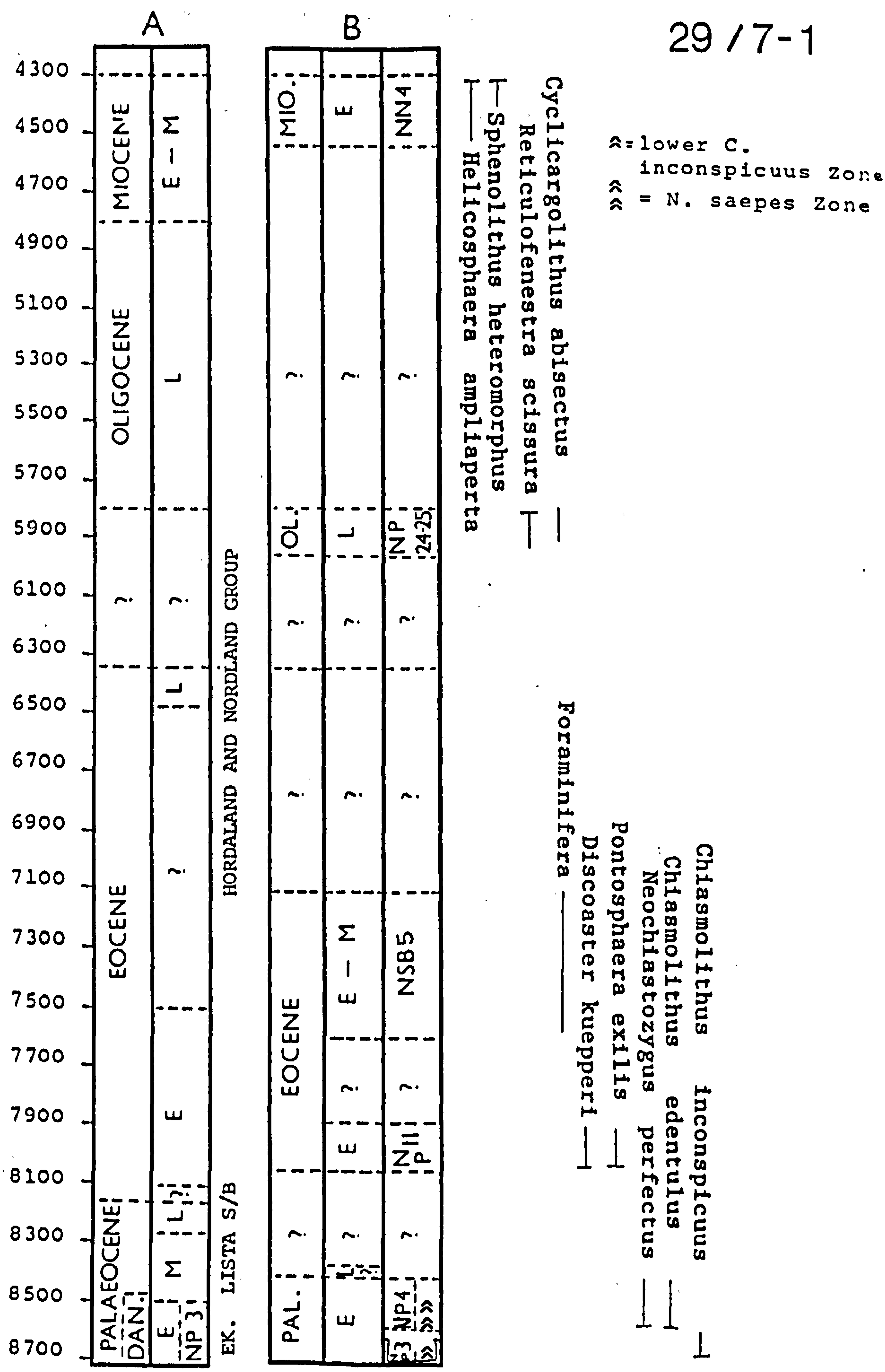
4. An enormous Palaeocene (>33% of total) interval existed which was completely devoid of calcareous nannofossils in its upper part (? deltaic), but yielded assemblages of similar age to those found in other wells in the lower part.

5. There is no obvious development of the Balder Formation.

6. The D10 and D12 (Shell/Esso notation, see Fig.27) log markers are present and can be used to tie in horizons from other wells.

**2.1.7 WELL NUMBER 29/7-1** (See Fig.28) : 17 SWS and 26 DC samples were analysed from this central North Sea Basin well. The SWS were evenly spread throughout the Palaeogene section of the well, but only DC's were available for the upper part. (See Appendix 1 for sample levels and lithology).

FIG. 28.


29 / 7-1
A
B
4300
4500
4700
4900
5100
5300
5500
5700
5900
6100
6300
6500
6700
6900
7100
7300
7500
7700
7900
8100
8300
8500
8700
MIOCENE
OLIGOCENE
EOCENE
PALAEOCENE
DAN.
E - M
L
E
M
NP 3
MIO.
OL.
NN4
NP 24-25
NSB5
NP 11
PAL.
NP4
HORDALAND AND NORDLAND GROUP
EK. LISTA S/B
Cyclicargolithus abisectus
Reticulofenestra scissura
Sphenolithus heteromorphus
Helicosphaera ampliaperta
Foraminifera
Chiasmolithus inconspicuus
Chiasmolithus edentulus
Neochiastozygus perfectus
Pontosphaera exilis
Discoaster kuepperi
» = lower C. inconspicuus Zone
»» = N. saepes Zone

**0000' - 4309' NOT SAMPLED**

This section was not sampled because the study of previous wells had shown that the Upper Miocene and Pliocene (according to the Completion Log) usually contained poorly consolidated sediment with just a few re-worked specimens, or are barren.

**4310' - 4550' EARLY MIOCENE**

This section was dated on the basis of a few DC samples only, but the association of Helicosphaera ampliaperta and Sphenolithus heteromorphus enabled accurate correlation with Martini's (1971) NN4 zone and Bukry's (1973) H. ampliaperta zone which covers the interval between the LDO of S. heteromorphus and the FDO of H. ampliaperta. The exact extent of this zone is uncertain due to the lack of further reliable marker species and the monotonous nature of the sediment pile (no foraminiferal analysis from this part of this well). It is possible, however, that some sort of boundary is marked by the limestone streaks at 4570' which then persist downhole at more or less regular intervals.

**4551' - 5979' BARREN**

The Completion Log showed a monotonous claystone sequence for this interval into which were interspersed occasional limestone streaks. All samples analysed were barren of calcareous nannofossils, but work on the foraminiferal assemblages by G.K. Gillmore is in progress and it is hoped that it will be used to divide this section biostratigraphically.

**5980' - 5990' ? LATE OLIGOCENE**

A single DC sample provided a sparse assemblage which, based on the association of Reticulofenestra scissura and Cyclicargolithus abisectus, can be dated as Late Oligocene, approximately equivalent to Martini's (1971) NP24/25 zones. the absence of the traditional Sphenolithus marker species made the sub-division of the Late Oligocene in the North Sea study material difficult.

**5991' ? - 7900' BARREN**

The Oligocene/Eocene boundary was not discernible as the interval was barren of calcareous nannofossils and no foraminiferal data are available yet. The deflection in the Gamma ray log at 8350' is a possible position for the boundary, but without further lithological or palaeontological evidence it remains conjectural.

**7901' - 8030' EARLY EOCENE**

The assemblage of calcareous nannofossils found in the two SWS's within this interval were diverse and moderately well-preserved. These specimens represented a period of time only occasionally preserved by the calcareous nannofossil record; this is equivalent to the Early Eocene NP11 zone of Martini (1971) with Discoaster kuepperi used as a marker in association with Pontosphaera exilis (see Steurbaut, 1988, p.101) to determine the age as being between Units II and IIIa of Steurbaut (1988), in the middle to upper part of zone NP11. This assemblage correlated quite well with that recovered from the London Clay of the London and Hampshire Basins (see Chapter 3 for details and discussion).

**8040' - 8120' BARREN**

This interval contained the Balder Formation; one of the most consistent lithological features of the North Sea Basin, and readily determined by its Gamma ray log response. It is however, barren of calcareous nannofossils and contained only a few indeterminate arenaceous foraminifera and diatoms.

**8121' - 8500' BARREN**

The Sele and Lista Formations are barren of calcareous nannofossils in this and in other wells studied. However, work on the foraminiferal assemblages is in progress, and it is hoped that some biostratigraphically useful forms will be recognised.

**8501' - 8540' EARLY PALAEOCENE**

A familiar assemblage, common to most of the wells studied in both the central and southern North Sea Basins, was recognised in this interval. The dominance of Chiasmolithus inconspicuus over Chiasmolithus danicus, in association with Prinsius martinii, and in the absence of Chiasmolithus edentulus, indicated an age equivalent to the lower C. inconspicuus Zone of Van Heck and Prins (1987).

**8541' - 8570' EARLY PALAEOCENE**

A slight change in the C2 assemblage (Van Heck and Prins, 1987) whereby Chiasmolithus danicus became dominant over Chiasmolithus inconspicuus indicated a change in age to the upper part of the NP3 zone of Martini (1971), the Neochiastozygus saepes Zone of Van Heck and Prins (1987), and the lower part of Perch-Nielsen's (1979) D9 zone.

**8571' - 8663' BARREN**

The samples analysed from the lower part of the Ekofisk Formation, although apparently identical in lithology to those from the upper part, are barren of calcareous nannofossils.

2.1.8 **WELL NUMBER 30/6-2** (See Fig.29) : 10 SWS and 27 DC samples were studied from this central North Sea Basin well, which lies close to the centre of

FIG. 29.


30/6-2

• = F. tympaniformis Zone
•• = upper C. inconspicuus Zone
•• = middle C. inconspicuus Zone

the present day basin. The samples were fairly evenly spread throughout the 9923' of Tertiary sediment in the well, but SWS were concentrated in the lower part, below the Balder Formation. No foraminiferal analysis was carried out on this well. (See Appendix 1 for sample levels and lithology).

**0000' - 2309' NOT SAMPLED**

**2310' - 3800' BARREN**

The light to medium grey claystone of the ditch cuttings in this interval proved to be almost completely barren of calcareous nannofossils, and hence of no biostratigraphical use. The Completion Log indicated that the Pliocene/Upper Miocene and Upper Miocene/Middle Miocene boundaries lay in this section, but in the absence of a reasonable nannofossil assemblage or a major lithological break they could not be proven. The Gamma ray log showed some change at the upper level, but was quite consistent overall. The very base of this section yielded a poor collection of calcareous nannofossils (including Helicosphaera sellii) which were probably caved from the presumed Late Miocene interval some way above.

**3801' - 5420' BARREN**

Marked as Lower / (Middle) Miocene on the Completion Log, this monotonous claystone interval, with occasional limestone and dolomite streaks, was almost completely devoid of calcareous nannofossils (a poor assemblage at 3800') and hence proved impossible to date accurately.

**5421' - 6500' MIOCENE/OLIGOCENE**

The top part of this interval (<5900') can be tentatively assigned an Early Miocene age as it contained the only reliable calcareous nannofossil assemblage (including Helicosphaera ampliaperta). The rest of the section was typical for the Miocene/Oligocene boundary zone in the central North Sea Basin in that it contained 'mixed' assemblages (extremely poor in this case, and taken from DC samples) of mainly Noelaerhabdaceae forms.

**8501' - 8430'** **LATE OLIGOCENE**

Such a large sedimentary interval (claystone of the Hordaland Group) could only be dated using a few DC samples, most of which proved to be barren. The Late Oligocene age was based on the familiar association of Reticulofenestra scissura and Cyclicargolithus abisectus, although in this well forms such as Chiasmolithus altus, Zygrhablithus bijugatus and Reticulofenestra scrippsae were conspicuous by their absence.

8431' - 9085' BARREN

The whole of the supposed Eocene section of this well (including the PT22 interval near the base) was barren of calcareous nannofossils, as is usual in this area of the North Sea Basin.

**9086' - 9237'** **BARREN**

The Balder Formation (ash marker) and Sele Formation were clearly indicated by their distinctive Gamma ray log responses, but as for all the previous wells these units proved to be barren of calcareous nannofossils.

**9238' - 9690'** **BARREN**

The Lista and Maureen Formations also proved to be barren for the most part (see following section for reference to the lower part of the Maureen Formation).

**9691' - 9720'** **LATE PALAEOCENE**

This interval of sediment (lowest Maureen Formation) yielded an assemblage of calcareous nannofossils which were unique amongst those recovered from the southern and central North Sea Basin study material in that they contained species of the genus Fasciculithus, in particular Fasciculithus tympaniformis. These could be used to date this section as equivalent to Martini's (1971) NP5 zone.

**9721' - 9760' EARLY PALAEOCENE**

This interval lacked the Fasciculithus species found above, but retained the association of Neochiastozygus perfectus and Chiasmolithus edentulus which enabled it to be dated as equivalent to Martini's (1971) NP4 zone. However, the preservation of the microfossils prevented a detailed analysis of the numbers of Neochiastozygus perfectus present, or a reliable count of the Chiasmolithus edentulus to Chiasmolithus inconspicuus ratio. Thus a sub-division into N. perfectus Zone or upper C. inconspicuus Zone (Van Heck and Prins, 1987) could not be made.

**9761' - 9800' EARLY PALAEOCENE**

The absence of Neochiastozygus perfectus from this interval indicated a change of zone. The continued presence of Chiasmolithus edentulus suggested that the change was a small one (within the NP4 zone of Martini, 1971) to the middle Chiasmolithus inconspicuus Zone. The Completion Log indicated that this section was NP3 zone (of Martini, 1971), but the high percentage presence of Chiasmolithus edentulus (in relation to other species of Chiasmolithus and Cruciplacolithus) indicated the equivalent of the NP4 zone.

**9801' - 9933' BARREN**

The remainder of the lower Palaeocene sediment (claystone intercalated with limestone) was barren of calcareous nannofossils (DC samples only).

**2.1.9 WELL NUMBER 30/19a-2** (See Fig.30) **:** 26 SWS and 17 DC samples were analysed from this central North Sea Basin well, which was also located near to the present day centre of the basin. No foraminiferal analysis was carried out on this well. See Appendix 1 for sample levels and lithology.

**0000' - 2913'** **NOT SAMPLED**

**2914' - 3509'** **BARREN**

This interval contained a monotonous series of grey siltstone and claystone (North Sea Clay Formation). No calcareous nannofossils were recovered thus the age inferred on the Completion Log (Upper Tertiary) cannot be confirmed.

**3510' - 3900'** **LATE MIOCENE/PLIOCENE**

Though poorly preserved and of very low diversity, the assemblages recovered from this section of claystone with limestone streaks had in common the presence of Helicosphaera sellii. This species is reported as having its FDO in the Pleistocene (e.g. Perch-Nielsen, 1985), but was only found commonly near the base of its range (Late Miocene) in the North Sea study material.

**3901' - 4620 ?** **MIDDLE/LATE MIOCENE**

The assemblages of calcareous nannofossils recovered from this interval did not contain Helicosphaera sellii, but did contain Reticulofenestra pseudoumbilicus and Calcidiscus leptoporus, thus Middle rather than Late Miocene is inferred. The position of the base of this zone is uncertain due to the poor quality of the assemblages, but may be taken at the increase in Gamma ray response at 4620'.

**4621' - 5700'** **BARREN / EARLY MIOCENE**

This extensive interval of sediment (claystone) contained 7 SWS which were analysed, but all proved to be barren of calcareous nannofossils. This is not

FIG.30.

30/19-2

• = upper C. inconspicuus Zone
•• = middle C. inconspicuus Zone
• = NP2
⁚ = NP1
Placozygus sigmoides
Cruciplacolithus tenuis
Neochiastozygus modestus
Chiasmolithus inconspicuus
Chiasmolithus edentulus
Neochiastozygus perfectus
Cyclicargolithus abisectus
Zygrhablithus bijugatus
Reticulofenestra scissura
Sphenolithus heteromorphus
Helicosphaera ampliaperta
Calcidiscus leptoporus
Reticulofenestra pseudoumbilicus
Helicosphaera sellii
A
B
MIO./ PLIO.
U
MIOCENE
E / M
OLIGOCENE / ? EOCENE
EOCENE
PAL. EOC.
PALAEOCENE
DAN.
E
L
NP 3/4
NORTH SEA CLAY FORMATION
TC CGCF TF
MIOCENE
L
M
NN 10?
NN 6-7
M-O
E
NN 4
OLIGOCENE
NP 24-25
PALAEOCENE?
NP 4
NP 3
2250
2500
2700
3000
3250
3500
3750
4000
4250
4500
4750
5000
5250
5500
5750
6000
6250
6500
6750
7000
7250
7500
7750
8000
8250
8500
8750
9250

unusual for the Oligocene/Eocene (from Completion Log) section of the North Sea study material, indeed, it would appear to fit the pattern observed in other wells. However, at 5580' and 5630' there are distinctive Early Miocene (equivalent to NN4 zone of Martini, 1971) assemblages in DC samples, which included Sphenolithus heteromorphus and Helicosphaera ampliaperta. It is possible that the Early Miocene assemblages are in situ and that a barren interval existed between the Middle and Early Miocene, with the Completion Log being incorrectly labelled as Oligocene/Eocene. Alternatively, and more likely, these assemblages may have been caved from around 4200'-4600' where the Early Miocene may have been missed by the SWS levels. The major limestone bands at 5600' and 5670' may indicate the position of the Miocene/Oligocene boundary in an otherwise monotonous lithological sequence.

**5701' - 7840' LATE OLIGOCENE**

Seven DC samples were analysed from this section, at approximately regular intervals, which yielded very poor calcareous nannofossil assemblages. The co-occurrence of Reticulofenestra scissura, Zygrhablithus bijugatus and Cyclicargolithus abisectus was used once again to indicate a Late Oligocene age, approximately equivalent to the NP24/25 zone of Martini (1971).

**7841' - 8441' BARREN**

The DC samples analysed in this interval were either barren of calcareous nannofossils, or contained specimens obviously caved from the Late Oligocene unit above.

**8442' - 8530' BARREN (inferred)**

The Thulean Tuff Formation (lateral equivalent of the Balder Formation) provided the usual distinctive Gamma ray log response, but was seen to contain a higher percentage of limestone than in other wells. It was not sampled as previous well material from this unit was consistently barren.

**8531' - 8960' EARLY PALAEOCENE**

The Central Graben Formation (Forties Group), lying directly above the Top Chalk Formation, yielded a good assemblage of calcareous nannofossils from the 3 SWS examined. The association of Neochiastozygus perfectus with Chiasmolithus edentulus (both in fairly high numbers) indicated the presence of the upper Chiasmolithus inconspicuus Zone (Van Heck and Prins, 1987).

**8961' - 9095' EARLY PALAEOCENE**

Below the distinctive D12 log marker (sonic and gamma ray responses) the Top Chalk Formation (lateral equivalent to the 'Danian' Ekofisk Formation) contained another good assemblage of calcareous nannofossils. The presence of Chiasmolithus edentulus in high numbers with Chiasmolithus inconspicuus was taken to indicate the middle C. inconspicuus Zone (Van Heck and Prins, 1987).

**9096' - 9152' EARLY PALAEOCENE**

The assemblages analysed in this interval showed a change in the type and proportions of the Chiasmolithus species present, and are generally less diverse than those in the sections immediately above. The presence of Chiasmolithus danicus, Chiasmolithus inconspicuus and Neochiastozygus modestus is taken to indicate a transition from the equivalent of the NP4 zone to the NP3 zone (Martini, 1971), but missing out the lower C. inconspicuus and Neochiastozygus saepes Zones of Van Heck and Prins (1987).

**9153' - 9180'** **EARLY PALAEOCENE**

Another reduction in the diversity of the calcareous nannofossil assemblage to leave only Cruciplacolithus tenuis and small Prinsius species indicated a further abrupt change to within the equivalent of Martini's (1971) NP2 zone.

**9181' - 9206'** **EARLY PALAEOCENE**

The base of the Early Palaeocene section is marked by a change in the chalk lithology. This change can be seen to also represent a change in age as the calcareous nannofossil assemblage changed from that in NP2 (above) to a very sparse association of Prinsius species with Placozygus sigmoides. This assemblage probably represents the equivalent of Martini's (1971) NP1 zone (in part), the D2 zone of Perch-Nielsen (1979) and the Placozygus sigmoides Zone of Van Heck and Prins (1987).

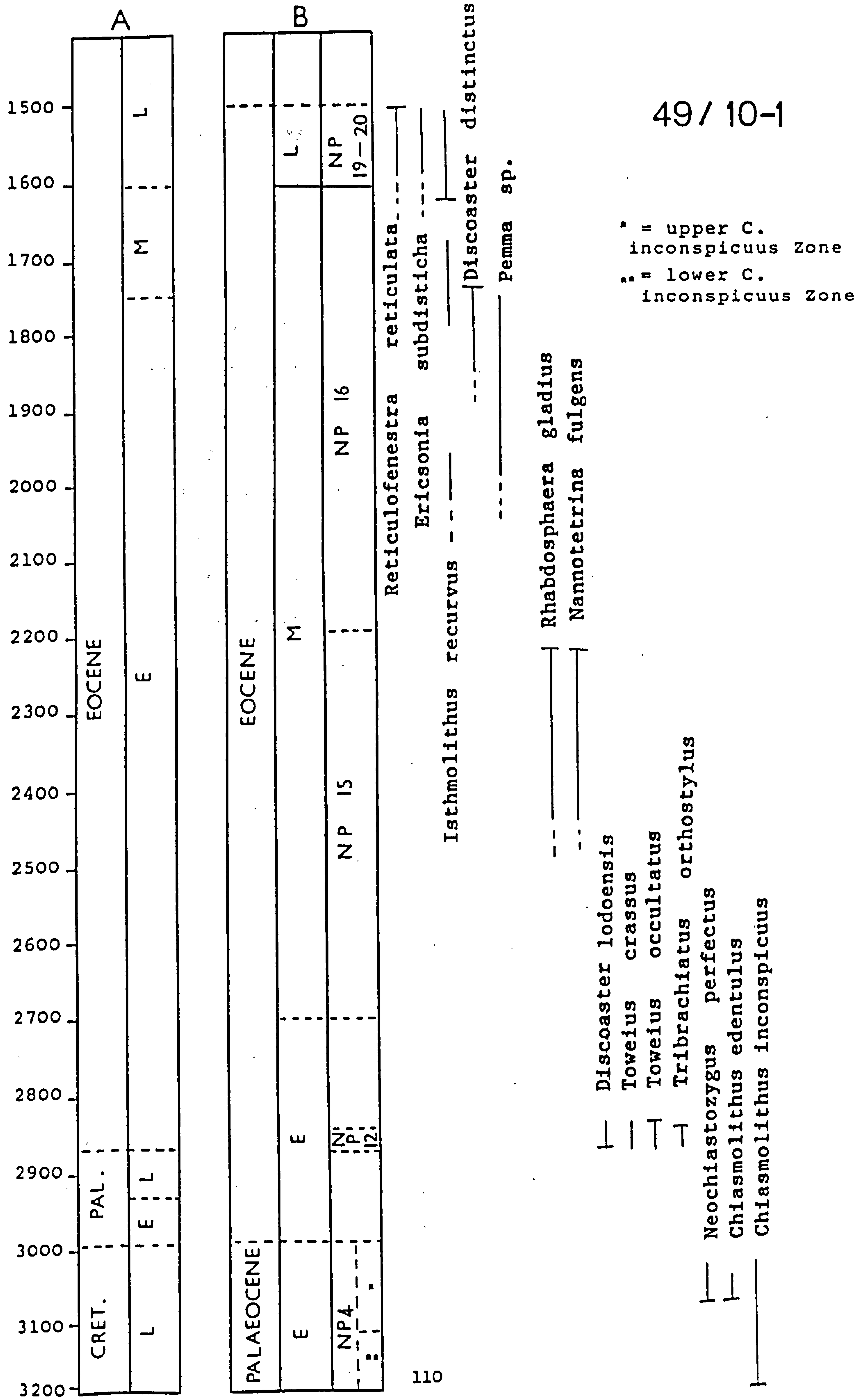
2.1.10 **WELL NUMBER 49/10-1** (See Fig.31) : 6 SWS and 8 DC samples were analysed from this southern North Sea well, in which the Tertiary sequence was restricted to approximately 1700' of Eocene and Palaeocene strata (approximately 1500' of which was Eocene). There was no analysis of foraminifera carried out for this well.(See Appendix 1 for sample levels and distribution chart.

**0000' - 1499'** **NOT SAMPLED**

**1500' - 1810'** **LATE EOCENE**

A very diverse and well-preserved calcareous nannofossil assemblage was found in this interval. As in wells 14/29-1 and 49/9-1, the co-occurrence of Reticulofenestra reticulata and Isthmolithus recurvus, together with Corannulus

FIG.31.



49/10-1
A
B
EOCENE
PAL.
CRET.
PALAEOCENE
L
M
E
NP 19–20
NP 16
NP 15
NP 12
NP 4
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
* = upper C. inconspicuus Zone
** = lower C. inconspicuus Zone
Reticulofenestra reticulata
Ericsonia subdisticha
Discoaster distinctus
Pemma sp.
Isthmolithus recurvus
Rhabdosphaera gladius
Nannotetrina fulgens
Discoaster lodoensis
Toweius crassus
Toweius occultatus
Tribrachiatus orthostylus
Neochiastozygus perfectus
Chiasmolithus edentulus
Chiasmolithus inconspicuus

germanicus and Ericsonia subdisticha, was taken to mark the presence of a zone equivalent to Martini's (1971) NP19/20 zone.

**1611' - 2199' MIDDLE EOCENE**

A number of species have their FDO in this interval, but their significance is confused by the fact that they have widely separated published extinction levels, although they come in at the same level in this well. Chiasmolithus oamaruensis was not present in well number 49/9-1, thus Martini's (1971) zone NP18 was presumed absent, but here it occurred with Pemma species and Discoaster distinctus, which have their FDO in NP16. It is proposed that this interval is in fact of Middle Eocene age, and that C. oamaruensis has been caved from some higher level. The apparent information gap between NP16 and NP19/20 was also observed in well number 49/9-1 and could be interpreted as a barren interval due to a lithological effect, or may indicate the presence of an unconformity not marked on the Completion Log.

**2200' - ? MIDDLE EOCENE**

The FDO of the very distinctive marker species Rhabdosphaera gladius was used to define the top of this interval, but in the absence of Nannotetrina species and Rhabdosphaera inflata it was not possible to put a lower limit on this interval above the level of the next identifiable unit at 2850'.

**2850' - 2880' EARLY EOCENE**

Once again (see wells 29/7-1 and 49/9-1) the lower part of the Eocene interval was dated in a thin interval of claystone containing a diverse assemblage of characteristic calcareous nannofossils. The association of Discoaster lodoensis, Towelus crassus and Tribrachiatus orthostylus was used to define the NP12 zone of Martini (1971), along with the relatively abundant and consistent presence of

Discoaster kuepperi and Towelus occultatus. The occurrence of Pontosphaera exilis in this interval can be used to limit the age to Unit V of Steurbaut (1988), just below the middle of the NP12 zone.

**2881' - 3003' BARREN**

This section represented the tuffaceous Balder Formation (distinctive gamma ray log response) and, as expected, the three SWS studied proved to be barren.

**3004' - 3210' EARLY PALAEOCENE**

The abundant occurrence of Neochiastozygus perfectus with the presence of Chiasmolithus edentulus and Chiasmolithus inconspicuus (42% and 21% of the C2 assemblage, of Van Heck and Prins, 1987, respectively) clearly indicated the presence of the upper Chiasmolithus inconspicuus Zone (Van Heck and Prins, 1987), which is approximately equivalent to the S1 zone of Perch-Nielsen (1979) and the middle of Martini's (1971) NP4 zone.

The lower part of this interval (3120' - 3210') may represent a slightly older level; the lower Chiasmolithus inconspicuus Zone, as neither Neochiastozygus perfectus nor Chiasmolithus edentulus were present.

**2.1.11 WELL NUMBER 29/3-1 and WELL NUMBER 49/19-1 :** 35 SWS and 0 DC samples were analysed for 29/3-1 in the central North Sea Basin, and 0 SWS and just 5 DC samples were analysed for 49/19-1 in the southern North Sea Basin.

49/19-1 has an extremely short Tertiary sequence (360') which consisted mainly of dark green glauconitic clays with muscovite and shell fragments. The nature of the sediment (unconsolidated) in this supposedly Eocene interval was not ideal for calcareous nannofossil analysis, and so it proved no surprise to find that the entire interval was barren, and therefore, undatable. Analysis for foraminifera, however, did recover some useful assemblages and the section was dated (G.K. Gilmore, pers. comm.) as Early to Middle Eocene (NSB3 - 5 zones of King, 1983).

The barren nature of all the samples taken from 29/3-1, however, was a little surprising as the well had many similar characteristics to the neighbouring wells 29/7-1 and 29/10-1, which both yielded calcareous nannofossil assemblages. The distribution of SWS's analysed was probably the reason for the barren nature of all the study material. Over 60% of the samples were taken from the Early Eocene and Late Palaeocene sections of the well (according to the Completion log = PT15-29) which were also barren in the other wells studied. Only one was taken in the Early Palaeocene chalk (Danian), and that was from a sandy interval near the base. This section was very fossiliferous in the other wells studied. It is very likely that a re-examination of this well, using DC's from higher up in the well intervals between the SWS levels, would reveal calcareous nannofossil assemblages of an age similar to those recovered from 29/10-1 and 29/7-1.

# COMPARATIVE MATERIAL

## RECOVERY AND INTERPRETATION

## 3.1 RECOVERY AND INTERPRETATION OF CALCAREOUS NANNOFOSSILS FROM COMPARATIVE MATERIAL.

The calcareous nannofossils recovered from each of the comparative localities are outlined below. Each locality is discussed with respect to previous work, and analysed in sections corresponding to identifiable stratigraphical intervals.

NB. Onshore sections are traditionally collected and subsequently discussed up-section, wheras the well sections discussed in Chapter 2 were investigated from the top downwards. For this reason the biostratigraphy of the comparative material is largely described using FOD's and LOD's :

FOD = First occurrence datum (inception) = LDO.

LOD = Last occurrence datum (disappearance or extinction) = FDO.

### 3.1.1 ST. STEPHEN'S QUARRY (LONE STAR CEMENT QUARRY), ST. STEPHEN'S, WASHINGTON COUNTY, ALABAMA,U.S.A. :

Description of the site location, geological setting and foraminiferal biostratigraphy can be found in Mancini and Copeland (1986).

There have been many previous investigations of this classic Eocene/Oligocene boundary section, among the more notable utilising calcareous nannofossils are by Roth (1970) and Siesser (1983).

A re-investigation of material collected from this site was carried out in order to review a number of Reticulofenestra species recorded here by Roth (1970) and, as a secondary project, to confirm the age of the section using calcareous nannofossils.

Fig.32. is a schematic lithological sketch section (after Lord, pers. comm.) showing the major rock units exposed in the North Quarry, with a description of the lithologies present in each formation (from Mancini and Copeland, 1986).

At St. Stephen's Quarry the Eocene/Oligocene boundary, based on the vertical distribution of planktonic foraminifera, occurred at the top of the Shubuta Clay Member of the Yazoo Clay Formation (Mancini and Copeland, 1986). The Eocene/Oligocene boundary is drawn worldwide at the top of the Globorotalia cerroazulensis (s.l.) Interval Zone (Stainforth et al., 1975), which at St. Stephen's Quarry closely approximated to the contact of the Shubuta Clay Member of the Yazoo Clay Formation with the Red Bluff Clay Formation.

Samples labelled A56 - A67 (see Fig.32. for distribution) were investigated for calcareous nannofossils, and the following biostratigraphical interpretation was made (see Table 7 for distribution of species) :

**A56 - A57 : LATE EOCENE** : A56 had quite an impoverished calcareous nannofossil assemblage relative to A57, but both contained Discoaster saipanensis and/or Discoaster barbadiensis, thus dating the Pachuta Marl Member (below the 'white' limestone band) of the Yazoo Formation as Late Eocene, equivalent to Martini's (1971) NP19/20 zone.

**A58 - A67 : EARLY OLIGOCENE** : The remainder of this section was dated as Ericsonia subdisticha zone (Roth, 1970) based on the LOD of E. subdisticha at A67 and the LOD of D. saipanensis / D. barbadiensis at A57. The LOD's of Lanternithus minutus, Ericsonia formosa and Isthmolithus recurvus also occurred in the top sample, which agrees quite well with the suggestion of Roth (1970) that these species become extinct in the lower part of his Cyclococcolithus margaritae zone, directly above the E. subdisticha zone.

Table. 7.

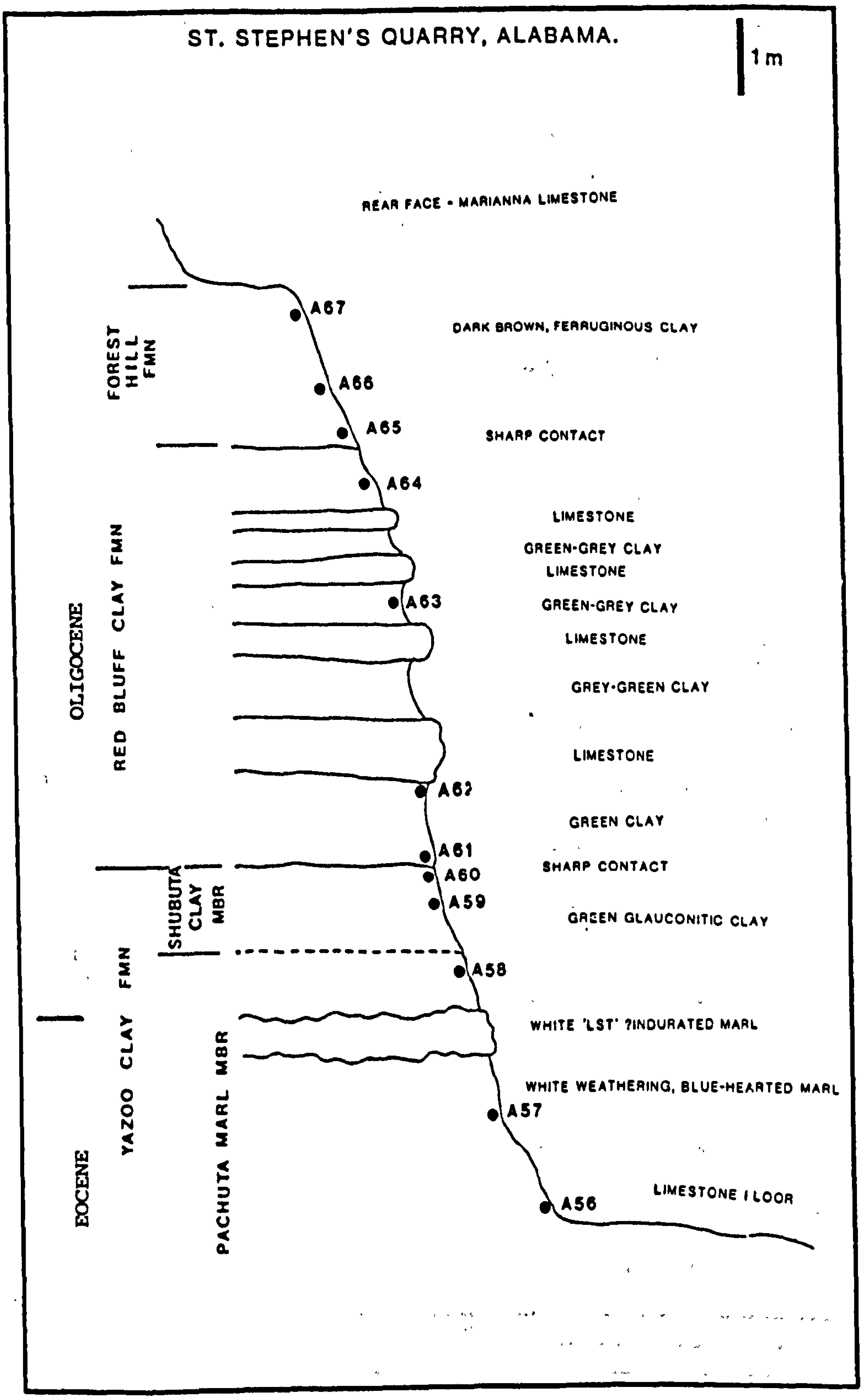
| A56 | A57 | A58 | A59 | A60 | A61 | A62 | A64 | A65 | A66 | A67 | SPECIES |
|---|---|---|---|---|---|---|---|---|---|---|---|
| X | X | X | X | X | X | X | X | X | X | X | Cyclicargolithus floridanus |
| X | X | X | X | X | X | X | X | X | X | X | Reticulofenestra minuta |
| X | X | X | X | X | X | X | X | X | X | X | Coccolithus pelagicus |
| X | X | X | X | X | X |  | X | X | X | X | Reticulofenestra scissura |
| X | X | X | X | X | X | X | X | X |  | X | Ericsonia subdisticha |
| X | X | X | X | X | X | X | X | X |  | X | Ericsonia formosa |
| X | X | X | X | X | X | X | X |  |  | X | Blackites spinosus |
| X | X | X | X | X | X | X | X | X |  |  | Transversopontis pulchra |
| X |  | X | X |  | X |  | X |  |  |  | Birkelundia staurion |
| X | X |  |  |  |  |  |  |  |  |  | Discoaster barbadiensis |
| X | X |  |  |  |  |  |  |  |  |  | Discoaster saipanensis |
|  | X |  |  |  |  |  |  |  |  |  | Pemma papillatum |
|  | X | X | X | X | X | X | X | X | X | X | Helicosphaera compacta |
|  | X | X | X | X | X | X | X | X | X | X | Helicosphaera euphratis |
|  | X | X | X | X | X | X | X | X |  | X | Sphenolithus moriformis |
|  | X |  | X |  | X | X | X | X | X | X | Lanternithus minutus |
|  | X | X | X | X | X |  | X | X | X | X | Helicosphaera reticulata |
|  | X | X |  |  | X | X | X | X |  | X | Reticulofenestra foveolata |
|  | X | X | X | X | X | X | X | X | X |  | Sphenolithus predistentus |
|  | X | X | X | X | X | X | X | X | X |  | Reticulofenestra umbilicus |
|  | X | X | X | X | X | X | X |  | X |  | Zygrhablithus bijugatus |
|  | X | X | X |  | X | X |  | X | X |  | Pontosphaera multipora |
|  | X | X | X |  | X | X | X | X |  |  | Reticulofenestra callida |
|  | X | X | X |  |  | X | X |  |  |  | Discoaster tanii |
|  | X |  |  |  | X | X | X |  |  |  | Markalius inversus |
|  | X |  | X |  |  |  | X |  |  |  | Braarudosphaera bigelowii |
|  | X | X | X | X | X | X |  |  |  |  | Reticulofenestra scrippsae |
|  | X | X | X |  | X | X |  |  |  |  | Isthmolithus recurvus |
|  | X | X | X |  | X | X |  |  |  |  | Transversopontis obliquipons |
|  | X | X |  |  | X | X |  |  |  |  | Pontosphaera wechesensis |
|  |  | X | X | X | X | X |  |  | X |  | Ericsonia obruta |
|  |  | X |  |  | X |  |  |  |  |  | Chiasmolithus titus |
|  |  | X |  |  |  |  |  |  |  |  | Bramletteius serraculoides |
|  |  | X |  |  |  |  |  |  |  |  | Reticulofenestra reticulata |
|  |  |  | X | X | X | X | X |  | X |  | Rhabdosphaera tenuis |
|  |  |  | X | X | X | X | X |  | X |  | Rhabdosphaera vitrea |
|  |  |  | X |  |  |  | X |  |  |  | Reticulofenestra laevis (c) |
|  |  |  |  |  | X | X | X | X | X |  | Discoaster deflandrei |
|  |  |  |  |  | X |  |  | X | X |  | Reticulofenestra oamaruensis |
|  |  |  |  |  | X | X | X | X |  |  | Orthozygus aureus |
|  |  |  |  |  | X | X |  |  |  |  | Pedinocyclus larvalis |
|  |  |  |  |  | X |  |  |  |  |  | Sphenolithus pseudoradians |
|  |  |  |  |  |  | X | X |  | X |  | Pontosphaera plana |
|  |  |  |  |  |  |  | X |  |  |  | Ilselithina fusa |
|  |  |  |  |  |  |  |  | X |  | X | Sphenolithus distentus (c) |

| | | |
|---|---|---|
| EOCENE | OLIGOCENE | AGE |
| LATE | EARLY | |
| NP 19/20 | NP 21 | (after Martini, 1971) |
| I.rec's | E. subdisticha | (after Roth, 1970) |

Table 7. Distribution of calcareous nannofossils from Alabama, and the age determination based on these assemblages.

(c) = contaminants

FIG. 32.




Lithological section with sample levels of Stephen's Quarry, Alabama.

re-drawn from Lord (unpub.) and Mancini and Copeland (1976).

It is clear from this investigation that there is a disparity between the Eocene/Oligocene boundary as defined by planktonic foraminifera (Yazoo Clay Formation/Red Bluff Clay Formation) and that defined by the calcareous nannofossil assemblages, where the LOD's of Discoaster saipanensis and Discoaster barbadiensis were taken to approximate the boundary in sections of this latitude.

This disparity has previously been noted by Bybell (1982) who placed the boundary at the disconformity in the Pachuta Marl Member of the Yazoo Clay Formation (= 'white limestone band' of this investigation). The difference in level for the Eocene/Oligocene boundary, 2.4 metres in this instance (between the 'white limestone band' in the Pachuta Marl and the Shubuta Clay/Red Bluff Clay contact), is not unusual; Gartner (1971), Stainforth and Lamb (1981), Poore et al. (1982), and Snyder et al. (1984) have all reported the boundary as occurring higher in the section when based on planktonic foraminifera as opposed to calcareous nannofossils.

The anomalously low occurrence of Reticulofenestra laevis and Sphenolithus distentus in this investigation suggested that there had been some contamination of the samples from the Byram Formation above.

Reticulofenestrids described by Roth (1970) from this section tended to be all in the region of 3.0um in diameter and, therefore, liable to confusion with one another particularly in the light microscope. Reticulofenestra minuta was abundant in sample A64, a short interval above its type level in the Red Bluff Clay Formation, and easily recognisable by the parameters set by Roth (1970) and those of Backman (1980). Reticulofenestra alabamensis is also easily recognised, but it is now thought to be a junior synonym of Reticulofenestra foveolata and the former name is no longer used. Reticulofenestra gabrielae and

Reticulofenestra pectinata, however, were not recognised from the topotype material (samples A64 and A65) and their validity is in some doubt. Further discussion of all these species appears in Chapter 4.

### 3.1.2 WILLIAM'S BLUFF (S136/898), OAMARU, OTAGO, NEW ZEALAND :

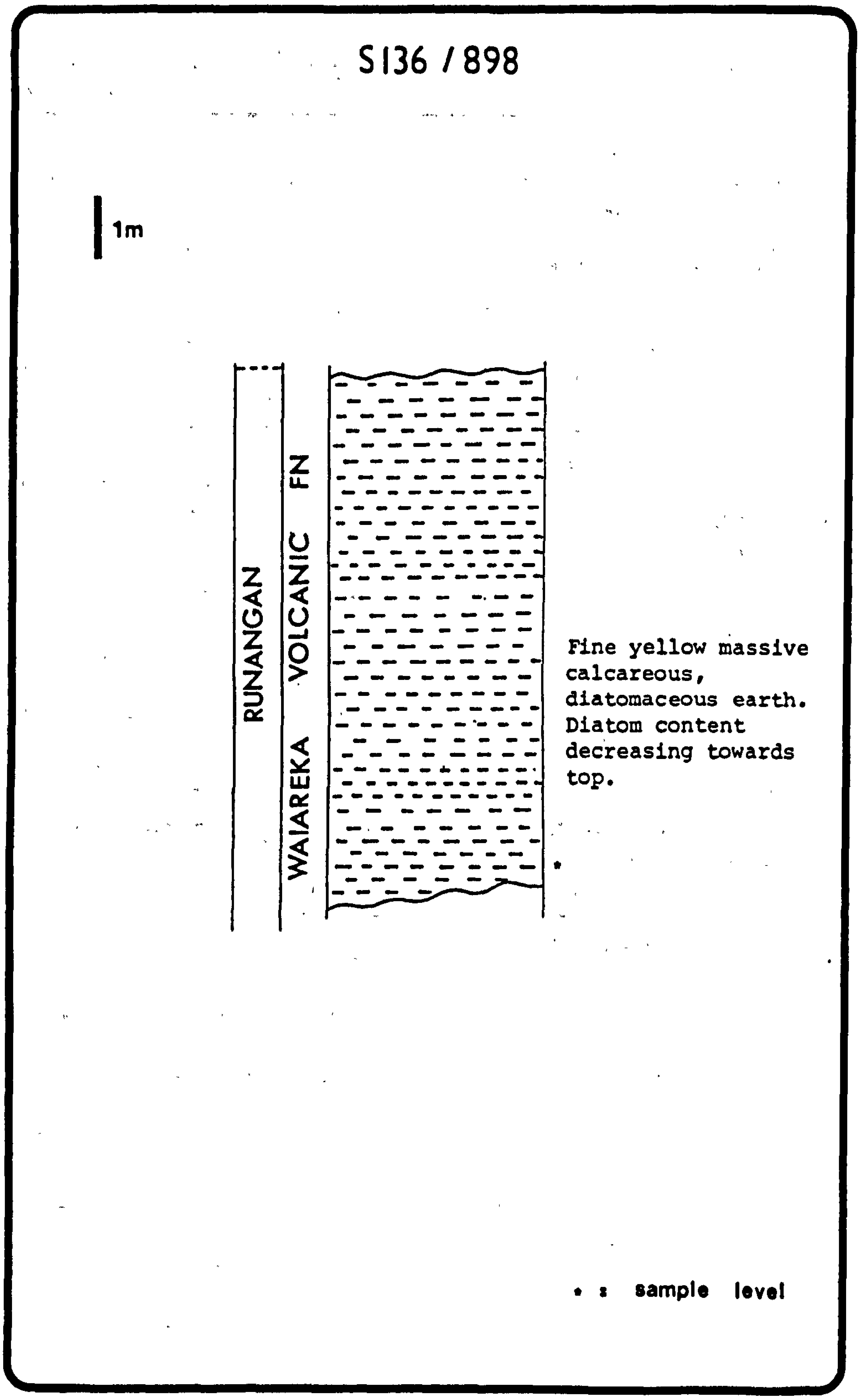
The Oamaru diatomite crops out at William's Bluff, near the top of the hillside, approximately one kilometre north of the old Lorne railway siding, and approximately 12 kilometres north of Oamaru (Stradner and Edwards, 1968). The diatomite at Oamaru represents one of the most widely studied outcrops of the southern hemisphere. More than 100 scientific papers have been written during the past 85 years (e.g. Deflandre and Fert, 1954; Bramlette and Riedel, 1954; Bramlette and Sullivan, 1961; Hay, Mohler and Wade, 1966; and Stradner and Edwards, 1968) detailing more than 1,000 species of microfossil from this diatomaceous mudstone. See Fig.33. for lithological log. The key microfossil (foraminifera and calcareous nannofossil) species from this locality were listed by Edwards in Stradner and Edwards (1968) and interpreted as Late Eocene (Runangan/Whaingaroan Stage) based on the association of Reticulofenestra oamaruensis, Isthmolithus recurvus and Discoaster saipanensis.

A list of the species identified in this investigation and an interpretation of the age of the sample is shown in Table 8.

### 3.1.3 HAMPDEN BEACH (HB728 - HB772), near OAMARU, NEW ZEALAND :

Samples from this location were extensively investigated by Edwards (1973). As a result it became the type locality for Reticulofenestra hampdenensis Edwards, and has subsequently been reviewed by Waghorn (pers. comm.).

FIG.33 .




Lithological section with sample level of S136/898, William's Bluff, Oamaru, New Zealand.



re-drawn from Stradner and Edwards (1968)

Table 8.

| SPECIES | AGE | | STAGE | ZONES # | ZONES @ |
|---|---|---|---|---|---|
| Zygrhablithus bijugatus * | LATE | EOCENE | RUNANGAN | R. OAMARUENSIS | NP 19/20 |
| Reticulofenestra coenura | | | | | |
| Cyclicargolithus floridanus | | | | | |
| Ericsonia formosa | | | | | |
| Reticulofenestra foveolata | | | | | |
| Reticulofenestra hillae | | | | | |
| Reticulofenestra minuta | | | | | |
| Lanternithus minutus | | | | | |
| Sphenolithus moriformis | | | | | |
| Pontosphaera multipora | | | | | |
| Chiasmolithus oamaruensis * | | | | | |
| Reticulofenestra oamaruensis * | | | | | |
| Transversopontis obliquipons * | | | | | |
| Coccolithus pelagicus | | | | | |
| Transversopontis pulcheroides | | | | | |
| Transversopontis pulchra | | | | | |
| Isthmolithus recurvus * | | | | | |
| Discoaster saipanensis * | | | | | |
| Reticulofenestra scissura | | | | | |
| Blackites spinosus | | | | | |
| Ericsonia subdisticha | | | | | |
| Reticulofenestra umbilicus * | | | | | |

Table 8. Shows the age determination of sample S136/898 based on the calcareous nannofossil assemblage.
* = species reported by Stradner and Edwards (1968).
# = informal zone of Stradner and Edwards (1968).
@ = 'standard' zone of Martini (1971).

No lithological log was available for this suite of samples, but a table of approximate correlations of stage names to formation names and ages was provided by Waghorn (see Table 9).

The distribution chart (see Table 10) for this locality illustrates the large number of well-preserved species recognised and the following stratigraphical interpretation is suggested.

**HB F728 - HB F748 :** **MIDDLE EOCENE :** There was a steady increase in the diversity of calcareous nannofossils up this section. Sample HB F728 from the Kurinui Formation was the least diverse, but still contained Chiasmolithus expansus, Discoaster sublodoensis and Discoaster saipanensis. The occurrence of Nannotetrina fulgens below the FOD of Reticulofenestra reticulata (see Waghorn in Perch-Nielsen, 1985a) was used to date this interval as equivalent to Martini's NP15 zone (unnamed by Waghorn in Perch-Nielsen, 1985a, p.434)). Specimens belonging to the 'Reticulofenestra hampdenensis' complex found in this section could be adequately referred to Reticulofenestra coenura and Reticulofenestra foveolata. These are known to have their FOD below that of Nannotetrina fulgens in New Zealand.

**HB F753 :** **MIDDLE EOCENE :** This sample contained the FOD of Reticulofenestra reticulata and occurred below the FOD of Reticulofenestra scissura. Such an association restricted it to the R. reticulata Zone of Waghorn in Perch-Nielsen (1985a), equivalent to NP16/17 of Martini (1971).

The division of this zone into a D. distinctus and a D. tanii sub-zone was not possible as the FOD of D. tanii was seen to occur before that of R. reticulata in this material. Reticulofenestra daviesii, a plugged form of 'Reticulofenestra hampdenensis' had its FOD in this sample.

Table 9.

| | | | |
|---|---|---|---|
| HB F772 | MOKIHI FORMATION | KAIATAN | LATE EOCENE |
| HB F768 | " | " | " |
| HB F763 | HAMPDEN FORMATION | BORTONIAN | MIDDLE EOCENE |
| HB F758 | " | " | " |
| HB F753 | " | " | " |
| HB F748 | " | " | " |
| HB F743 | " | " | " |
| HB F738 | " | " | " |
| HB F733 | " | " | " |
| HB F728 | KURINUI FORMATION | ? | MIDDLE EOCENE |

adapted from Waghorn (unpub.)

Table 9. Distribution of samples from the Kurinui, Hampden, and Mokihi Formations of Hampden Beach, and their approximate ages.

Table. 10.

| HBF728 | HBF733 | HBF738 | HBF743 | HBF748 | HBF753 | HBF758 | HBF763 | HBF768 | HBF772 | SPECIES |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | SAMPLE LEVELS | | | | | | |
| X | X | X | X | X | X | X | X | X | X | Coccolithus pelagicus |
| X | X | X | X | X | X | X | X | X | X | Ericsonia formosa |
| X | X | X | X | X | X | X | X | X | X | Cyclicargolithus floridanus |
| X | X | X | X | | X | X | X | X | X | Transversopontis pulcheroides |
| X | X | | | | | X | X | X | X | Discoaster barbadiensis |
| X | X | X | X | X | X | X | X | X | | Chiasmolithus solitus |
| X | X | X | X | X | X | X | X | X | | Neococcolithes dubius |
| X | | | | | X | X | X | X | | Chiasmolithus expansus |
| X | X | X | | | | X | X | | | Reticulofenestra hillae |
| X | X | X | X | X | X | X | | | | Reticulofenestra dictyoda |
| X | X | X | X | X | X | | | | | Discoaster distinctus |
| X | | X | X | | X | | | | | Discoaster tanii |
| X | X | | | | X | | | | | Discoaster saipanensis |
| X | | X | | | X | | | | | Discoaster sublodoensis |
| | X | X | X | X | X | X | X | X | X | Reticulofenestra umbilicus |
| | X | X | X | X | X | X | X | X | X | Sphenolithus moriformis |
| | X | X | X | X | X | X | X | X | X | Reticulofenestra minuta |
| | X | X | X | X | X | X | X | X | X | Reticulofenestra foveolata |
| | X | X | X | | | X | | X | X | Transversopontis pulchra |
| | X | X | X | X | | X | X | X | | Ericsonia fenestrata |
| | X | | | | | | | | | Nannotetrina fulgens |
| | | X | X | X | | X | X | X | X | Blackites spinosus |
| | | X | X | X | | X | X | X | X | Zygrhablithus bijugatus |
| | | X | X | | | X | X | X | X | Pontosphaera multipora |
| | | X | X | | | X | | X | | Lanternithus minutus |
| | | X | X | X | | X | | | | Neococcolithes minutus |
| | | | X | X | X | X | X | X | X | Reticulofenestra coenura |
| | | | X | X | | X | X | X | X | Transversopontis obliquipons |
| | | | X | | X | X | | | | Helicosphaera dinesenii |
| | | | X | | | | | | | Rhabdosphaera vitrea |
| | | | | X | | | | | | Reticulofenestra daviesii |
| | | | | | X | X | X | X | X | Reticulofenestra reticulata |
| | | | | | | X | X | X | X | Reticulofenestra scissura |
| | | | | | | X | X | X | | Discoaster binodosus |
| | | | | | | X | | | | Sphenolithus predistentus |
| | | | | | | X | | | | Rhabdosphaera gladius |
| | | | | | | X | | | | Helicosphaera compacta |
| | | | | | | X | | | | Rhabdosphaera pseudomorionum |
| | | | | | | | | X | X | Ericsonia subdisticha |
| | | | | | | | | X | X | Chiasmolithus oamaruensis |
| | | | | | | | | | X | Isthmolithus recurvus |
| EOCENE | | | | | | | | | | AGE |
| MIDDLE | | | | | | | | LATE | | |
| NP15 | | | | | NP16 | NP17 | | NP18 | NP19 | (with respect to Waghorn in Perch-Nielsen, 1985 and Martini, 1971) |

Table.10. illustrates the distribution of calcareous nannofossils in samples from Hampden Beach, New Zealand, and the age determination based on these assemblages.

HB F758 - HB F763 : MIDDLE EOCENE : The LDO of Reticulofenestra scissura was used by Waghorn in Perch-Nielsen (1985a) to mark the base of the R. scissura zone, and is employed herein for the same purpose. This assemblage of calcareous nannofossils (equivalent in age to Martini's (1971) NP17 zone) also included Rhabdosphaera pseudomorionum, Helicosphaera compacta, Rhabdosphaera gladius (stratigraphically higher than would be expected in north-west European sections) and Ericsonia obruta. There were no new additions to the 'Reticulofenestra hampdenensis' complex above this level.

HB F768 LATE EOCENE : The move from the Hampden Formation to the Mokihi Formation was reflected in a move from the Reticulofenestra scissura zone to the Chiasmolithus oamaruensis zone, based on the LDO of Chiasmolithus oamaruensis (Waghorn in Perch-Nielsen, 1985a). This zone which also contained the LDO of Ericsonia subdisticha can be equivalated to Martini's (1971) NP18 zone.

HB F772 LATE EOCENE : The stratigraphically highest sample of this section contained a diverse assemblage of calcareous nannofossils, including the LDO of Isthmolithus recurvus. As this species occurred with Reticulofenestra reticulata, the sample can be dated as being in the Reticulofenestra coenura sub-zone, of the Isthmolithus recurvus zone (Waghorn in Perch-Nielsen, 1985a) which is equivalent to the NP19 zone of Martini (1971).

Further discussion of species relating to 'Reticulofenestra hampdenensis' can be found in Chapter 4.

**3.1.4 JOIDES 5 (501), BLAKE PLATEAU, 554' 10" below top :**

In 1965 six cores were taken on the Florida continental shelf, on the Florida-

In 1965 six cores were taken on the Florida continental shelf, on the Florida-Hatteras slope, and on the Blake Plateau, by the drilling vessel M.V. Caldrill while involved in the JOIDES Deep Earth Sampling Programme (Roth, 1970).

Hole 5 (30°23'N,80°08'W) contained the thickest Oligocene section and consisted of whitish-grey calcilutites. It has been studied previously by Hay et al. (1967) and Roth (1968,1970) for the establishment of a zonation scheme. Sample 501 (554'10" below top) was dated as Early Oligocene (Ericsonia subdisticha zone) by Roth (1970) on the presence of Ericsonia subdisticha and the absence of Eocene discoaster species (i.e. Discoaster barbadiensis and Discoaster saipanensis). Re-investigation of this sample confirms this age assignment on the basis of an abundant presence of Ericsonia subdisticha and the FOD of Sphenolithus predistentus, which has its inception in the Early Oligocene (E. subdisticha zone) according to Roth (1970), see Table 11.

The primary reason for analysing this sample was to examine specimens of the Cyclicargolithus floridanus / Cyclicargolithus abisectus complex in the scanning electron microscope. The stratigraphic level of this sample was too low for C. abisectus to be present, but specimens of C. floridanus could be measured and compared with C. abisectus from other localities (including the North Sea Basin). Detailed discussion of this investigation can be found in Chapter 4.

### 3.1.5 XXth EUROPEAN MICROPALAEONTOLOGICAL COLLOQUIUM; PALAEOGENE OF THE ISLE OF WIGHT :

Knowledge of the calcareous nannofossil content of Palaeogene formations of north-west Europe is now quite well advanced. Pioneer work within the Anglo-Paris Basins was carried out by Bramlette and Sullivan (1961), Hay and Mohler

Table 11.

| SPECIES | AGE | | STAGE | ZONES | |
|---|---|---|---|---|---|
| | | | | # | @ |
| Braarudosphaera bigelowii * | | | L | | |
| Zygrhablithus bijugatus * | E | O | | | |
| Reticulofenestra callida | | | A | | |
| Helicosphaera euphratis * | | L | | E | N |
| Cyclicargolithus floridanus * | | | T | • | |
| Pyrocyclus hermosus * | A | I | | | |
| Reticulofenestra minuta * | | | D | S | |
| Lanternithus minutus * | | G | | U | P |
| Sphenolithus moriformis * | | | O | B | |
| Pontosphaera multipora * | R | O | | D | |
| Coccolithus pelagicus | | | R | I | |
| Sphenolithus predistentus * | | C | | S | 2 |
| Sphenolithus pseudoradians | | | F | T | |
| Reticulofenestra scissura * | L | E | | I | |
| Helicosphaera seminulum * | | | I | C | |
| Lithostromation simplex | | N | | H | 1 |
| Blackites spinosus | | | A | A | |
| Ericsonia subdisticha * | Y | E | | | |
| | | | N | | |

Table 11. Age determination for JOIDES 5 (501) 554' 10" below top based on the calcareous nannofossil assemblage recovered.
* = species also reported by Roth (1970).
# = zone defined by Roth (1970).
@ = 'standard' zone of Martini (1971).

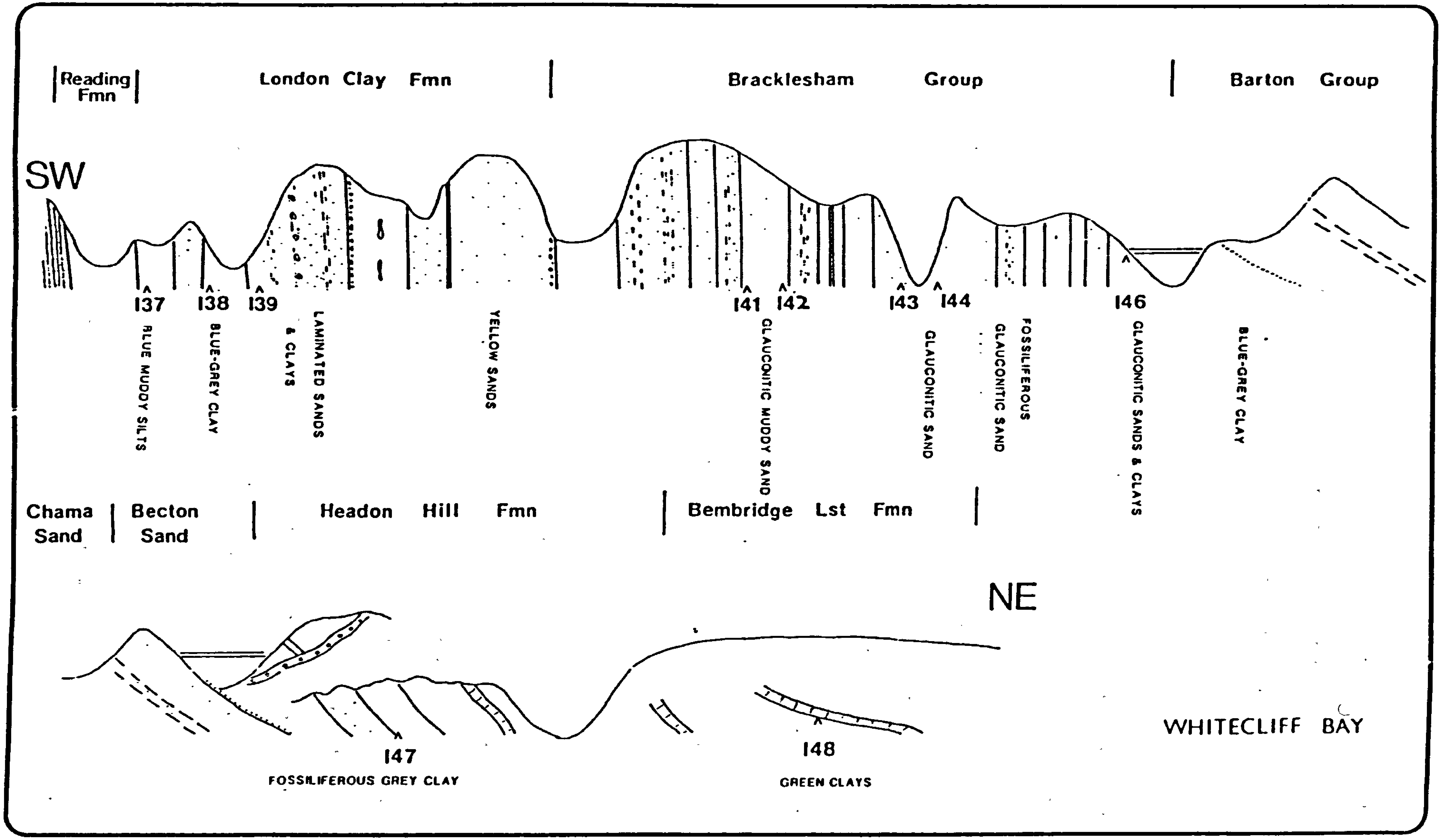
(1967), and Hodson and West (1975). In 1971 Martini used localities in southern England as reference sites for his Standard Tertiary Zonation Scheme and more recently Hamilton and Hojjatzadeh (1982) and Aubry (1983, 1986) have made detailed studies of Palaeogene sections from the classic north-west European sites.

The samples analysed for this study have yielded assemblages of calcareous nannofossils which show close similarity with those reported by Aubry (1986) and correlate reasonably well with assemblages from other north-west European Basins, in particular the southern North Sea Basin (49/9-1 and 49/10-1), the central North Sea Basin (29/7-1 and 21/11-1), and the London Basin (London Clay Formation of the London area).

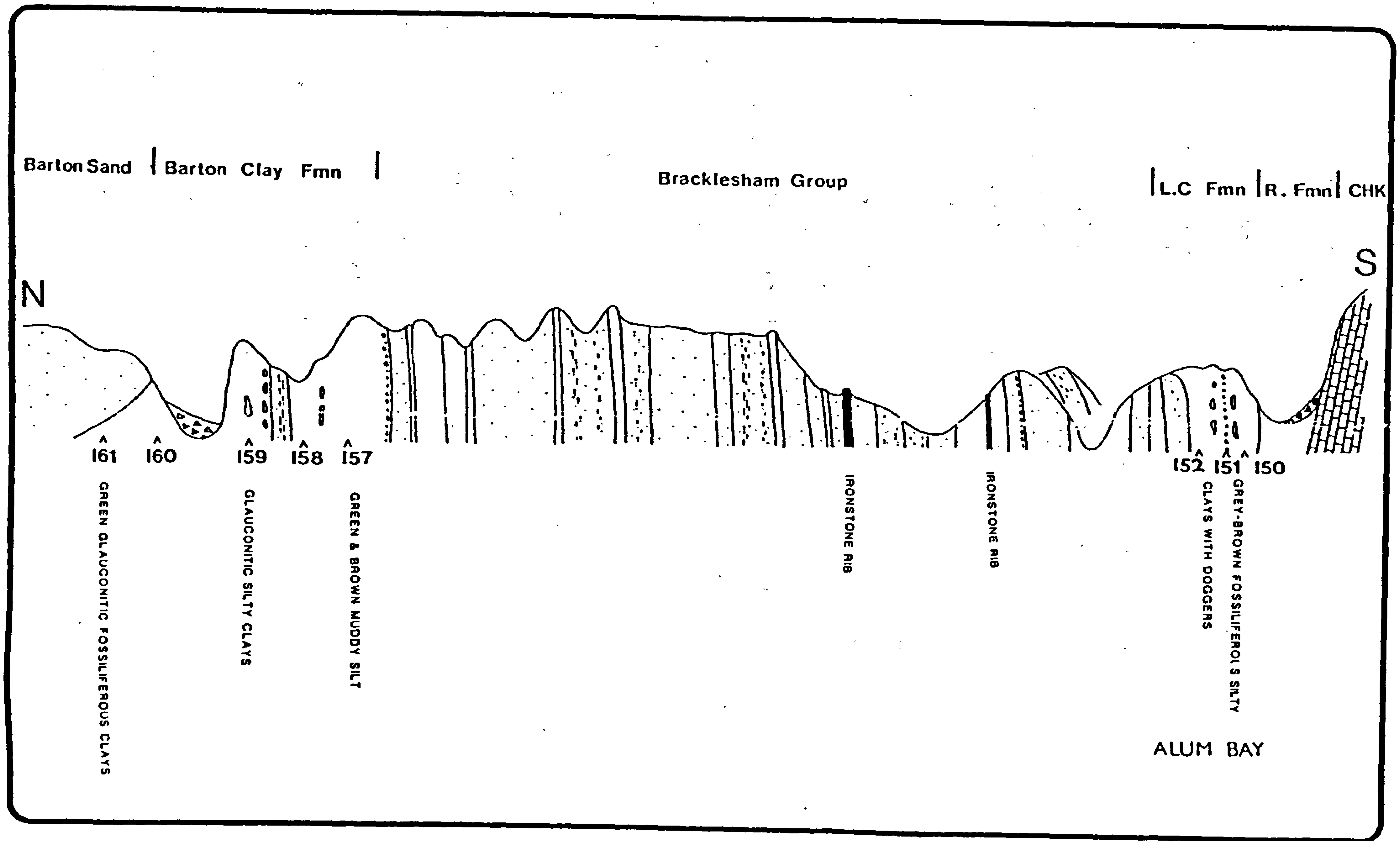
The number of barren intervals interspersed with the levels in which calcareous nannofossils were recovered indicated that the Hampshire Basin was probably of a marginal marine disposition and its high-latitude location and localised calcareous nannofossil content may well merit the erection of a regional biozonation scheme.

The section at Whitecliff Bay covers one of the most stratigraphically continuous Palaeogene sections in western Europe (see Fig.34). Within a distance of just over one kilometre approximately 600 metres of late Palaeocene to early Oligocene strata are exposed (Daley and Insole, 1984). The cliffs of Alum Bay and Headon Hill (see Fig.35) exhibit a complete sequence from the Upper Chalk through the Upper Palaeocene to Upper Eocene beds.

A suite of samples collected by Prof. J.W. Murray was studied by all the contributors to the Colloquium, see Table 12 for distribution of calcareous nannofossil samples. The oldest beds which contain calcareous nannofossils are of an age equivalent to Martini's (1971) NP12 zone (= Early Eocene) based on the




Schematic lithological section with sample points of Whitecliff Bay. Re-drawn from Murray et al (1987) FIG. 34




Schematic lithological section with sample points of Alum Bay. Re-drawn from Murray et al (1987).

FIG. 35 .

Table 12.

| LOCALITY | | LOCALITY | | LOCALITY | |
|---|---|---|---|---|---|
| I 37 | B | I 46 | | I 57 | |
| I 38 | B | I 47 | B | I 58 | |
| I 39 | B | I 48 | B | I 59 | |
| I 41 | B | I 49 | | I 60 | |
| I 42 | | I 50 | B | I 61 | |
| I 43 | B | I 51 | | I 62 | B |
| I 44 | | I 52 | B | I 64 | |

Table 12. Sample locality numbers used in this study.

B = Barren samples.

first occurrences of Discoaster kuepperi (as a replacement for the rare or absent Discoaster lodoensis - Aubry, 1986, p.279). The best preserved assemblage of this age was recovered from Fisher Bed IV at Bracklesham, where species of Toweius, Sphenolithus and Discoaster occur in a moderately diverse association.

By far the most abundant and diverse assemblages occurred in beds dated as NP15/16 (equivalent) zones of the Middle Eocene. Fisher Bed XVII at Bracklesham was particularly interesting for its association of Pemma and Nannotetrina species, probably reflecting a nearshore environment.

See Table 13 for distribution of species.

### 3.1.5.1 WHITECLIFF BAY :

The Palaeogene succession was deposited in environments varying from continental to shallow marine. The frequent facies changes throughout the succession cause lateral variation in lithology (Murray, *in* Murray *et al.*, 1987). The cliffs are being actively eroded and consequently the cliff line at present lies some tens of metres landward of that measured in detail by Fisher in 1862. See Gallagher *in* Lord and Bown (1987) for full discussion of these samples.

**Samples I37 - I39** : Brown - blue silty clay. Early Eocene, London Clay Formation. 14.3m above base of formation to 11.0m below the pebble bed - Barren of calcareous nannofossils, but interpreted as Early Eocene (London Clay Formation, A3-C1 zones of King, 1981, p.76) by Murray (*in* Murray *et al.*, 1987).

**Sample I41** : Glauconitic, muddy sand. Early Eocene, Bracklesham Group, Wittering Formation, Fisher Bed IV, 1.0m above base of bed - Barren of calcareous nannofossils in this study, but reported as equivalent to Martini's (1971) NP12 zone, by Aubry (1986, p.293).

Sample I42 : Blue sandy clay, Early Eocene, Bracklesham Group, Wittering Formation, Fisher Bed IV, 1.0m from top - Preservation of the calcareous nannofossil assemblage was quite good, but abundance and diversity was very low. The age of the assemblage was equivalent to the NP12 zone of Martini (1971) based upon the first occurrence of Discoaster kuepperi (as a replacement for the rare or absent Discoaster lodoensis, used by Aubry, 1986, p.279). This sample is probably equivalent to Unit V of Steurbaut (1988).

Sample I43 : Blue sandy clay, Middle Eocene, Bracklesham Group, Earnley Formation, Fisher Bed VI (Eaton Bed 10a) - Barren of calcareous nannofossils, but a good assemblage of dinoflagellate cysts (Eaton, in Murray et al., 1987, p.160) was used to date this sample.

Sample I44 : Fossiliferous blue sandy clay, Middle Eocene, Bracklesham Group, Earnley Formation, Fisher Bed VI, 24.0m above lignitic top of Bed V - A good assemblage of calcareous nannofossils was recovered from this sample. An age equivalent to Martini's (1971) NP14/15 zone is deduced based on the FOD of Reticulofenestra dictyoda, Reticulofenestra callida and Cyclicargolithus floridanus. Some re-working from older horizons was evident.

Sample I46 : Brown clay, Middle Eocene, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base - The occurrence of Discoaster wemmelensis, Nannotetrina species, Pemma basquensis and Reticulofenestra dictyoda in the assemblage indicated an age equivalent to the NP15 zone of Martini (1971). This was the most abundant and diverse assemblage recovered from this suite of samples. Some re-working of Cretaceous forms evident.

Sample I47 : Brown fossiliferous clay, Late Eocene, Solent Group, Headon Hill Formation, Colwell Bay Member - Barren of calcareous nannofossils, but contained abundant foraminifera, ostracods and dinoflagellate cysts which were used to date the sample (Murray et al., 1987, p.163-164)

**Sample I48 :** Micritic limestone, Late Eocene, Solent Group, Bembridge Limestone Formation - Barren of all the major microfossil groups. Only Charophytes available in sufficient numbers to date the sample.

**Sample I49 :** Shell-rich clay, Early Oligocene, Solent Group, Bouldner Formation, Bembridge Marls Member - A very poor assemblage, possibly re-worked, contained only Discoaster binodosus and a few Reticulofenestra species.

### 3.1.5.2 ALUM BAY :

The Late Palaeocene Reading Formation rests unconformably on an irregular surface cut in the Campanian chalk. The Palaeogene succession extends up to the Late Eocene Barton Group and is well exposed in the cliff section (Murray et al., 1987). Although the Reading and London Clay Formations are similar in development to their occurrence in Whitecliff Bay, the Bracklesham Group is quite different, being composed of sands interbedded with lignitic clays. The Wittering, Earnley Sand, Marsh Farm and Selsey Sand Formations cannot be distinguished. The Barton Clay Formation and Barton "Sands" are well-exposed.

**Sample I50 :** Grey silty clay, Early Eocene, London Clay Formation, Division A3 of King (1981, p.92), 10.0m above the base of the formation - Barren of calcareous nannofossils, but dated by the association of foraminifera, ostracods, and dinoflagellate cysts (see Murray et al., 1987).

**Sample I51 :** Grey silty clay, Early Eocene, London Clay Formation, 21.6m above the base of the formation and 0.5m above the pebble bed at the base of B1 = planktonic datum - An impoverished assemblage of calcareous nannofossils including Neococcolithes dubius and Towelus pertusus, indicated an age equivalent to Martini's (1971) NP11/12 zones.

**Sample I52** : Grey silty clay, Early Eocene, London Clay Formation, Division B2 of King (1981, p.92), 36.6m above the base of the formation and 15.0m above the pebble bed at the base of B1 - Barren of calcareous nannofossils, but dated by a combination of foraminifera and dinoflagellate cysts (see Murray et al., 1987).

**Sample I57** : Grey clay, Middle Eocene, Barton Clay Formation, 16.0m above conglomeratic pebble bed - A reasonably diverse assemblage of calcareous nannofossils was recovered from this sample. The association of Pemma basquensis, Neococcolithes dubius, and Reticulofenestra umbilicus inferred an age perhaps equivalent to the NP15/16 zone of Martini (1971).

**Sample I58** : Grey clay, Middle Eocene, Barton Clay Formation, approximately 26.0m above the conglomeratic pebble bed - A reasonably diverse assemblage of calcareous nannofossils (similar to that recovered from I57) was recovered from this sample. The presence of the Reticulofenestra species assemblage in association with Neococcolithes dubius indicated the NP15/16 zones of Martini (1971).

**Sample I59** : Grey clay, Late Eocene, Barton Clay Formation, approximately 39.0m above the conglomeratic pebble bed - The FOD of Reticulofenestra reticulata in an otherwise unchanged assemblage of calcareous nannofossils was used to indicate the incoming of zone NP17 of Martini (1971).

**Sample I60** : Brown clay, Late Eocene, Barton Clay Formation, 3.0m to the north of the steps - A relatively abundant assemblage of calcareous nannofossils containing <u>Reticulofenestra</u> <u>reticulata</u>, indicated the presence of the NP17 zone of Martini (1971).

**Sample I61** : Late Eocene, Barton Clay Formation, 5.0m below the junction with the Barton "Sand" - Abundant re-worked Cretaceous specimens in an impoverished <u>in situ</u> assemblage containing <u>Reticulofenestra</u> <u>umbilicus</u>. the sample was dated using a combination of the microfossil groups analysed.

### 3.1.5.3 HEADON HILL :

The slopes of Headon Hill above the white sands of the Barton "Sand" are disturbed by landslips, but it is possible to piece together the lower part of the Headon Hill Formation (Murray <u>et</u> <u>al</u>., 1987) see Fig.36.

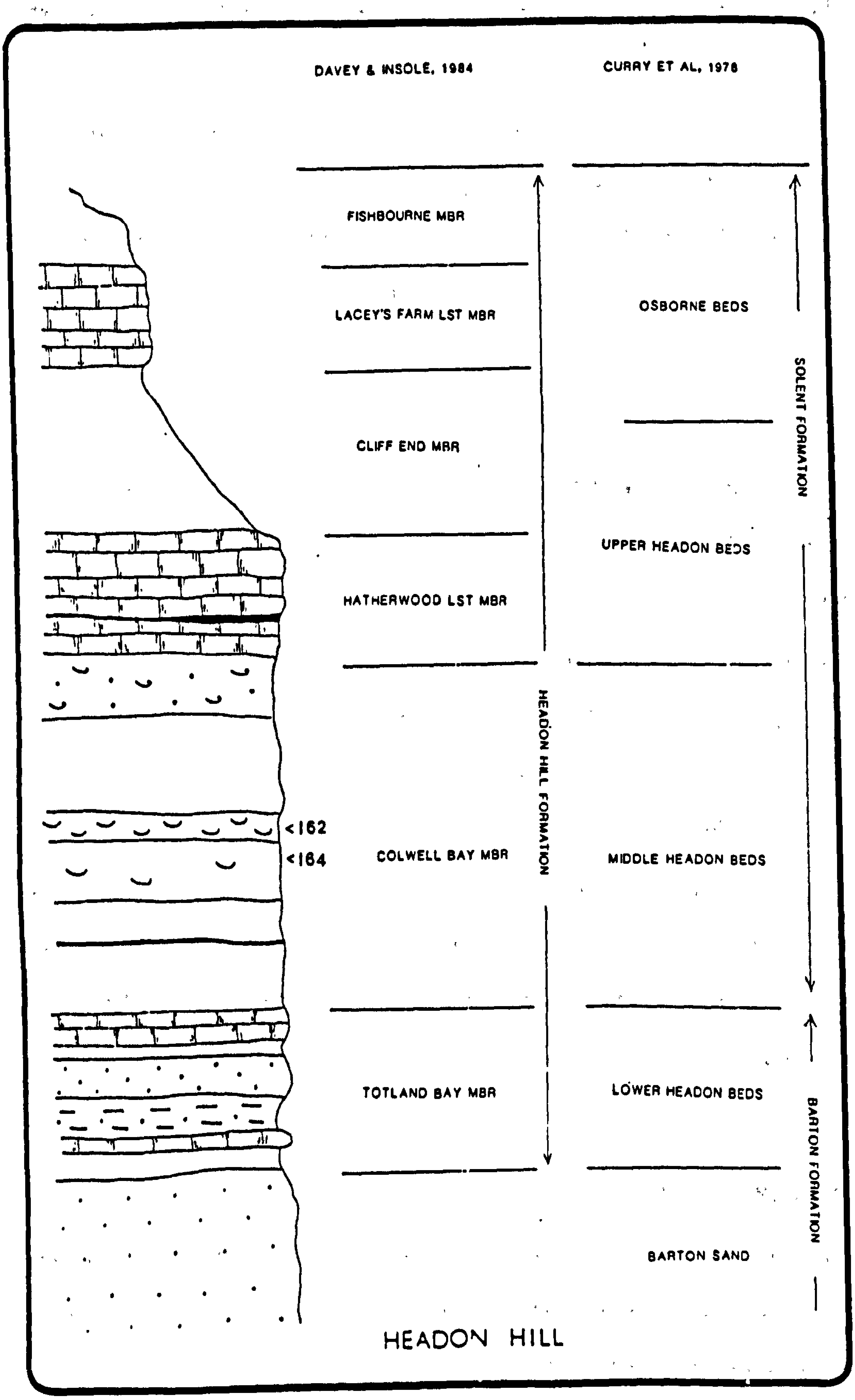
**Sample I62** : Oyster-rich clay, Late Eocene, Solent Group, Headon Hill Formation, Colwell Bay Member - Barren of calcareous nannofossils, but dated as Late Eocene using foraminifera, ostracods and dinoflagellate cysts (see Murray <u>et</u> <u>al</u>., 1987, p.177-178).

**Sample I63** : Micritic limestone, Late Eocene, Solent Group, Headon Hill Formation, Hatherwood Limestone Member - Barren of calcareous nannofossils, and very low in other microfossil groups. Only charophytes were well represented.

### 3.1.5.4 COLWELL BAY :

The low cliffs expose a section through the Headon Hill Formation from the top of the Totland Bay Member, through the Colwell Bay Member to the Hatherwood Limestone Member (Murray <u>et</u> <u>al</u>., 1987).

FIG. 36 .




Lithological section with sample points of the NE corner of Headon Hill. Re-drawn from Murray et al (1987).

Table.13.

| I37 | I38 | I39 | I50 | I51 | I52 | I41 | I42 | I43 | I44 | I46 | I57 | I58 | I59 | I60 | I61 | I47 | I48 | I49 | I62 | I63 | I64 | SPECIES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | X | | | X | | X | X | X | X | X | X | X | | | | | | | Coccolithus pelagicus |
| | | | | X | | | | | | X | | X | | X | | | | | | | | Braarudosphaera bigelowii |
| | | | | X | | | | | X | X | X | X | | | | | | | | | | Neococcolithes dubius |
| | | | | X | | | | | | | | | | | | | | | | | | Toweius pertusus |
| | | | | X | | | | | | | | | | | | | | | | | | Transversopontis rectipons |
| | | | | | | | X | | X | X | X | X | X | X | X | | | | | | X | Reticulofenestra minuta |
| | | | | | | | X | | | | | | | | | | | X | | | | Discoaster binodosus |
| | | | | | | | X | | X | X | X | X | X | X | X | | | | | | | Transversopontis pulchra |
| | | | | | | | X | | | X | | | | | | | | | | | | Discoaster distinctus |
| | | | | | | | X | | X | | | | | | | | | | | | | Sphenolithus radians |
| | | | | | | | X | | | | | | | | | | | | | | | Discoaster kuepperi |
| | | | | | | | X | | | | | | | | | | | | | | | Toweius occultatus |
| | | | | | | | X | | | | | | | | | | | | | | | Campylosphaera dela |
| | | | | | | | | | X | X | X | X | X | X | X | | | | | | | Blackites spinosus |
| | | | | | | | | | X | X | X | X | X | | | | | | | | | Reticulofenestra coenura |
| | | | | | | | | | X | X | X | | | | | | | | | | | Reticulofenestra dictyoda |
| | | | | | | | | | X | | X | | | | | | | | | | | Cyclicargolithus floridanus |
| | | | | | | | | | X | | | | | | | | | | | | | Reticulofenestra callida |
| | | | | | | | | | | X | X | X | X | X | X | | | | | | X | Reticulofenestra umbilicus |
| | | | | | | | | | | X | | | | | | | | | | | X | Reticulofenestra hillae |
| | | | | | | | | | | X | | X | X | X | | | | | | | | Lanternithus minutus |
| | | | | | | | | | | X | X | X | | X | | | | | | | | Pemma basquensis |
| | | | | | | | | | | X | | | X | X | | | | | | | | Zygrhablithus bijugatus |
| | | | | | | | | | | X | | | | X | | | | | | | | Discoaster wemmelensis |
| | | | | | | | | | | X | | | | X | | | | | | | | Neococcolithes minutus |
| | | | | | | | | | | X | | X | | | | | | | | | | Goniolithus fluckigeri |
| | | | | | | | | | | X | | X | | | | | | | | | | Micrantholithus vesper |
| | | | | | | | | | | X | | | | | | | | | | | | Chiasmolithus expansus |
| | | | | | | | | | | X | | | | | | | | | | | | Discoaster barbadiensis |
| | | | | | | | | | | X | | | | | | | | | | | | Ericsonia formosa |
| | | | | | | | | | | X | | | | | | | | | | | | Lithostromation perdurum |
| | | | | | | | | | | X | | | | | | | | | | | | Markalius inversus |
| | | | | | | | | | | X | | | | | | | | | | | | Nannotetrina fulgens |
| | | | | | | | | | | X | | | | | | | | | | | | Nannotetrina nitida |
| | | | | | | | | | | X | | | | | | | | | | | | Pontosphaera multipora |
| | | | | | | | | | | X | | | | | | | | | | | | Reticulofenestra scissura |
| | | | | | | | | | | | X | X | | X | | | | | | | | Reticulofenestra foveolata |
| | | | | | | | | | | | | | X | X | | | | | | | | Ericsonia fenestrata |
| | | | | | | | | | | | | | X | X | | | | | | | | Reticulofenestra reticulata |
| | | | | | | | | | | | | | | X | | | | | | | | Ericsonia subdisticha |
| | | | | | | | | | | | | | | | | | | | | | X | Discoaster saipanensis |
| ? | | | | NP11-12 | ? | | NP12-13 | ? | NP14-16 | | | NP17 | | | | ? | | NP17 | ? | | NP19 ? | AGE zones after Martini (1971) and Aubry (1983,1986). |

Table.13. illustrates the distribution of calcareous nannofossils in samples from Whitecliff Bay, Alum Bay, Headon Hill, Colwell Bay on the Isle of Wight, and their age determination based on these assemblages.

**Sample 164 :** Late Eocene, Solent Group, Headon Hill Formation, Colwell Bay Member - A very low diversity calcareous nannofossil assemblage containing Discoaster saipanensis, could only be used to supplement the age assignment based on other fossil groups.

**3.1.6 DSDP Leg 12 Site 117-2-3 (147-148cm)** (see Fig.37):

Site 117 lies on the boundary between the Hatton-Rockall Basin and the Rockall Bank (57°20.17'N,57°23.97'W). Bukry (pers. comm.) suggested that the sample 117-2-3 (147-148cm) from this site would be ideal to study Chiasmolithus altus due to its abundant presence and good preservation.

This sample was dated as Late Oligocene (NP25, Sphenolithus ciperoensis zone, Martini, 1971) by Perch-Nielsen (1972b) even though Chiasmolithus altus was the only species recorded which was of biostratigraphical use and Sphenolithus ciperoensis was absent. During analysis of this sample for the elucidation of the taxonomic characteristics of Chiasmolithus altus (see Chapter 4 for discussion) the assemblage was examined as a matter of routine and a number of species which more definitely indicate a Late Oligocene age (NP24/25 zones of Martini, 1971) were observed, i.e. Cyclicargolithus abisectus, Helicosphaera recta, Chiasmolithus altus and Reticulofenestra scissura (see Table 14).

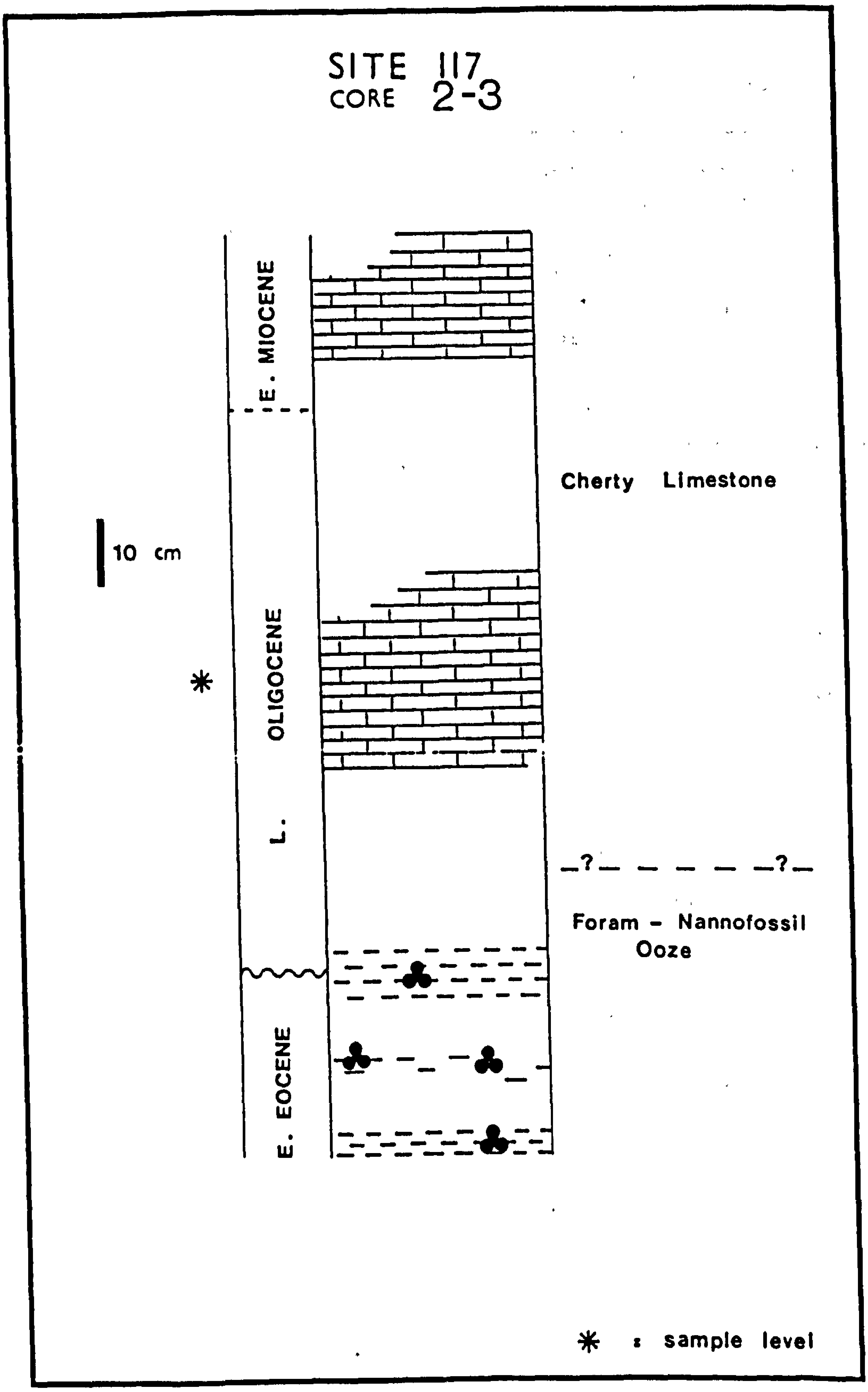
It was interesting to observe that this high-latitude sample contained a Late Oligocene assemblage of calcareous nannofossils which was similar to those recovered from the North Sea Basin, and appeared to have little in common with those of lower latitudes which commonly contain Sphenolithus marker species.

Table.14

| SPECIES | AGE | | STAGE | ZONES | |
|---|---|---|---|---|---|
| | | | | # | @ |
| | | O | | | |
| Cyclicargolithus abisectus | | | C | S | |
| Chiasmolithus altus * | | L | | . | |
| Zygrhablithus bijugatus | L | | H | | N |
| Reticulofenestra coenura | | I | | C | |
| Sphenolithus compactus | | | A | I | |
| Discoaster deflandrei | A | G | | P | P |
| Cyclicargolithus floridanus * | | | T | E | |
| Helicosphaera intermedia | | O | | R | |
| Reticulofenestra minuta | T | | T | O | 2 |
| Coccolithus pelagicus * | | C | | E | 4 |
| Sphenolithus moriformis | | | I | N | / |
| Helicosphaera recta | E | E | | S | 2 |
| Reticulofenestra scissura | | | A | I | 5 |
| Reticulofenestra scrippsae | | N | | S | |
| | | | N | | |
| | | E | | | |

Table 14. Age determination for ODP-12-117-2-3 (147-148cm) based on the calcareous nannofossil assemblage recovered.
* = species also reported by Perch-Nielsen (1972).
# and @ = 'standard' zone defined by Martini (1971).

FIG .37 .




Position and lithology of sample 117-2-3 (147-148cm)

**3.1.7 DSDP Leg 36 Site 329-29-1 (138-139cm) and 329-30-2 (132-133cm)** (See fig.38a,b) :

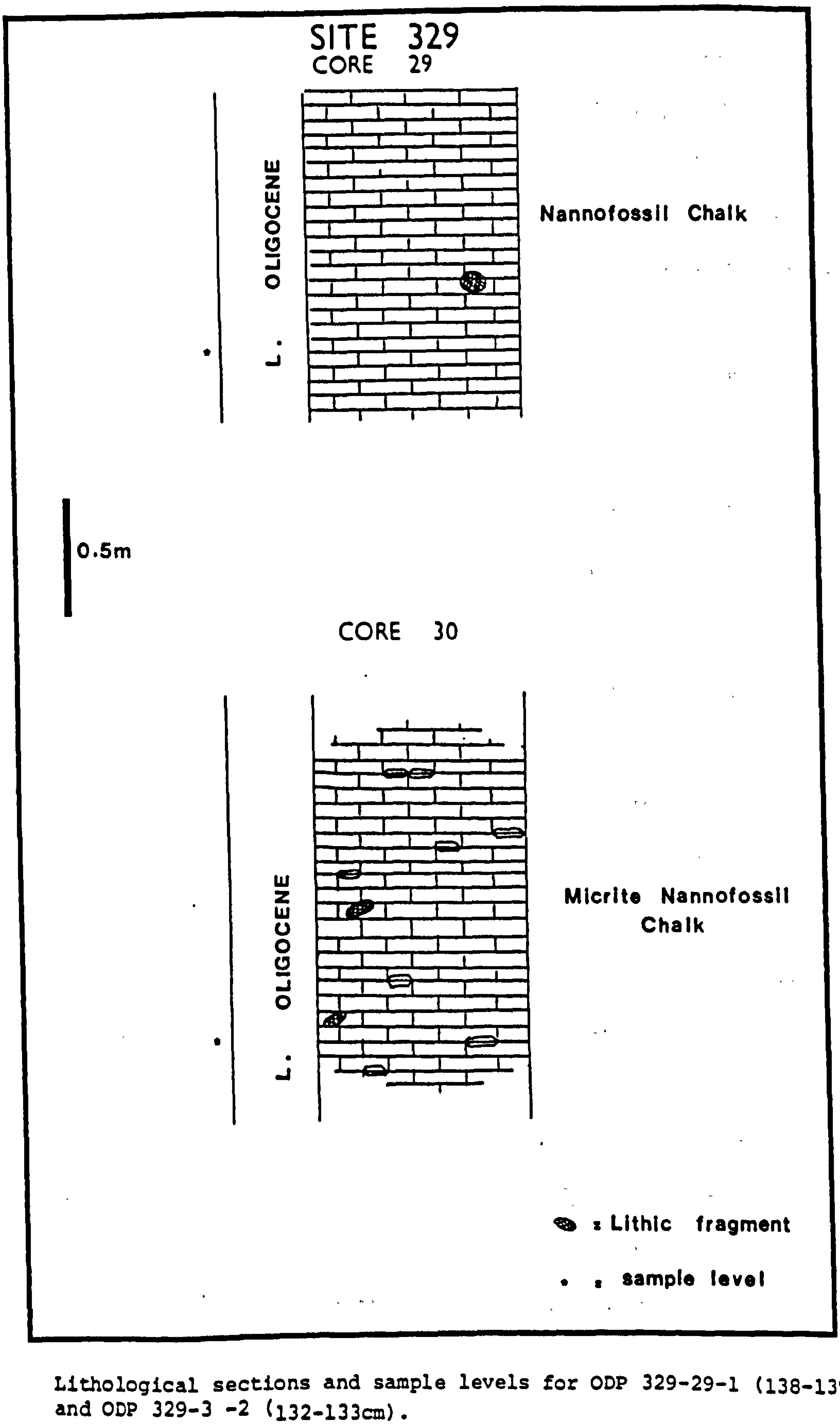
Site 329 on the Maurice Ewing Bank, in the South Atlantic Ocean (50°39.31'S,46°05.73'W) was also suggested by Bukry (pers. comm.) as a suitable locality to study the taxonomy and stratigraphic distribution of Chiasmolithus altus. As in sample 12-117-2-3, this species occurred abundantly in very well-preserved, although not diverse assemblages from these localities. Once again a Late Oligocene age was suggested by the association of Cyclicargolithus abisectus, Reticulofenestra scissura and Chiasmolithus altus (see Table 15a,b).

**3.1.8 LONDON CLAY FORMATION, LONDON BASIN** :

**3.1.8.1 PARLIAMENT HILL FIELDS** (See Table 16) :

**Sample B2** : This sample proved to be the youngest of those from Parliament Hill Fields which yielded calcareous nannofossils, based on the occurrence of Discoaster kuepperi in association with Toweius occultatus, Tribrachiatus orthostylus and Pontosphaera ocellata. The age was equivalent to Martini's (1971) NP12 zone, and Unit V of Steurbaut (1988).

**Samples 1-7** : As all these samples were recovered from the spoil heap of a tunnel excavation it was not possible to determine their relative stratigraphic positions, however, as the tunnel was being driven at a low angle, through very gently dipping strata, it was assumed that all came from approximately the same stratigraphical level. Samples numbered 1,4 and 6 were barren of calcareous nannofossils, but the samples numbered 2,3,5 and 7 contained assemblages of a similar age, thought to be equivalent to Martini's (1971) NP11 zone based on the association of Toweius occultatus and Tribrachiatus orthostylus and in the




Lithological sections and sample levels for ODP 329-29-1 (138-139cm) and ODP 329-3 -2 (132-133cm).
(Re-drawn from Barker et al, 1976).

Table 15a

| SPECIES | AGE | | STAGE | ZONES | |
|---|---|---|---|---|---|
| | | | | # | @ |
| | | O | | S | |
| Cyclicargolithus abisectus | L | L | C | . | N |
| Chiasmolithus altus | | I | H | | P |
| Reticulofenestra coenura | A | G | A | C | |
| Cyclicargolithus floridanus | | O | T | I | 2 |
| Reticulofenestra minuta | T | C | T | P | 4 |
| Coccolithus pelagicus | | E | I | ' | / |
| Reticulofenestra scissura | E | N | A | S | 2 |
| | | E | N | | 5 |

Table 15b

| SPECIES | AGE | | STAGE | ZONES | |
|---|---|---|---|---|---|
| | | | | # | @ |
| Chiasmolithus altus | L | | | S | N |
| Zygrhablithus bijugatus | | O | | . | |
| Reticulofenestra coenura | | L | C | | |
| Cyclicargolithus floridanus | A | I | H | C | P |
| Reticulofenestra hillae | | G | A | I | |
| Markalius inversus | | O | T | P | |
| Reticulofenestra minuta | T | C | T | E | 2 |
| Sphenolithus moriformis | | E | I | R | 4 |
| Coccolithus pelagicus | | N | A | ' | / |
| Reticulofenestra scissura | E | E | N | S | 2 |
| Reticulofenestra scrippsae | | | | | 5 |

Table 15a. Age determination for ODP-36-329-29-1 (138-139cm) based on the calcareous nannofossil assemblage recovered.
Table 15b. Age determination for ODP-36-329-30-2 (132-133cm) based on the calcareous nannofossil assemblage recovered.
# and @ = 'standard' zone defined by Martini (1971).

absence of *Discoaster lodoensis, Discoaster kuepperi* and *Tribrachiatus contortus* (Aubry, 1986, p.279).

The samples from Parliament Hill Fields represented one of the few attainable calcareous horizons in the London Clay Formation, and yielded a relatively well-preserved and diverse assemblage of calcareous nannofossils (and of foraminifera and dinoflagellate cysts; G.K. Gillmore and J.G.S. Goodall, *pers. comm.*).

The narrow age range of these assemblages partly reflected the limited available material, but may also be an indication of the amount of time during which nannoplankton were able to survive in the obviously restricted environment of the London Clay Sea. (See Table 16 for species distribution).

The Early Eocene age accorded with those suggested by the foraminiferal and organic-walled microplankton data (G.K. Gillmore and J.G.S. Goodall, *pers. comm.*) and could be correlated with age assignments for well material in both the southern (49/9-1) and central North Sea Basins (29/7-1).

### 3.1.8.2 LORD'S ROUNDABOUT, ALBANY TERRACE, NEW BRITISH LIBRARY SITE, BEDFORD SQUARE

Five samples were analysed from the New British Library site at King's Cross, and a single sample from each of the other localities. All of these samples proved to be barren of calcareous nannofossils, although a few did contain organic-walled microplankton and foraminifera (G.K. Gillmore and J.G.S. Goodall, *pers. comm.*). It is assumed that these samples were either from unfossiliferous horizons or were taken at levels which had been affected by weathering effects (i.e. <3m below the surface).

Table.16.

| PH 1 | PH 2 | PH 3 | PH 4 | PH 5 | PH 6 | PH 7 | B 2 | BL 1 | BL 2 | BL 3 | BL 4 | BL 5 | ALBY | LORD | BEDS | SPECIES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | X | | X | | | | | | | | | | | | Sphenolithus anarrhopus |
| | | | | | | X | | | | | | | | | | Discoaster barbadiensis |
| | X | X | | X | | | | | | | | | | | | Braarudosphaera bigelowii |
| | | X | | | | X | X | | | | | | | | | Discoaster binodosus |
| | X | X | | | | X | | | | | | | | | | Toweius crassus |
| | X | X | | X | | X | X | | | | | | | | | Neococcolithes dubius |
| | | | | | | X | | | | | | | | | | Sphenolithus editus |
| | | X | | X | | | | | | | | | | | | Micrantholithus inaequalis |
| | | | | | | | X | | | | | | | | | Discoaster kuepperi |
| | | | | X | | X | | | | | | | | | | Sphenolithus moriformis |
| | | | | X | | X | X | | | | | | | | | Neococcolithes minutus |
| | X | X | | X | | X | X | | | | | | | | | Toweius occultatus |
| | | X | | | | | X | | | | | | | | | Pontosphaera ocellata |
| | X | X | | X | | | X | | | | | | | | | Tribrachiatus orthostylus |
| | X | X | | X | | X | X | | | | | | | | | Coccolithus pelagicus |
| | | X | | X | | X | X | | | | | | | | | Toweius pertusus |
| | | X | | | | | | | | | | | | | | Sphenolithus primus |
| | | | | | | X | X | | | | | | | | | Sphenolithus radians |
| | X | X | | X | | X | X | | | | | | | | | Transversopontis rectipons |
| EARLY EOCENE | | | | | | | | ? | | | | | | | | AGE |
| NP11 | | | | | | | NP12 | ? | | | | | | | | ZONE (Martini,1971) |

PH = Parliament Hill
BL = British Library
ALBY = Albany Terrace
LORD = Lord's Roundabout
BEDS = Bedford Square

Table 16. Distribution of calcareous nannofossils in the London Clay samples and their age determination.

### 3.1.9 PEGWELL BAY :

This classic Late Palaeocene section (Thanetian type area) has been thoroughly examined for calcareous nannofossils in the past (e.g. Bramlette and Sullivan, 1961; Hay and Mohler, 1967; Hamilton, 1982 and Aubry, 1983). More recently, Godfrey (1984), Godfrey and Lord (1984), and Siesser, Ward and Lord (1987) have reviewed the biostratigraphy of the sections at Pegwell Bay and Herne Bay - Reculver. The main conclusion from which was the confirmation of the Thanetian stratotype as NP6/7 and NP8 zones (Martini, 1971) in age.

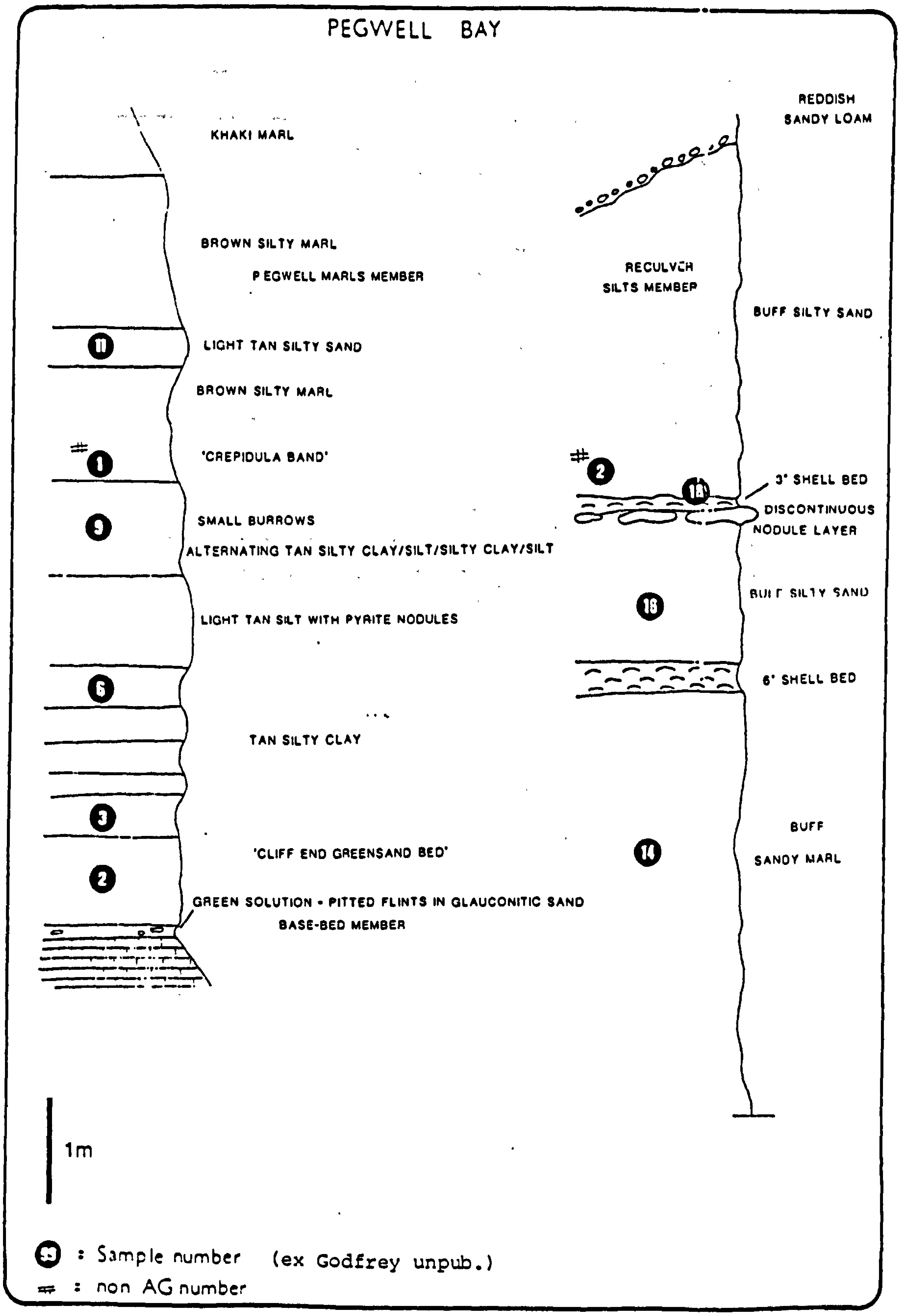
These samples (see Fig.39) were examined primarily for their relatively high abundance of Towelus species, the detailed structural properties of which were examined as part of a detailed study of the Noelaerhabdaceae lineage (see Chapter 4).

The assemblages of calcareous nannofossils recovered from these samples are listed in Table 17 and their biostratigraphy is discussed below;

**AG2, AG3, AG6, AG9, AG18, AG20** : These samples from the Base-bed Member, Stourmouth Clays Member, and Reculver Silts Member of the Thanet Formation at Pegwell Bay (see Fig.39) were all barren of calcareous nannofossil assemblages. Siesser, Ward and Lord (1987, p.92-93) reported a thin layer of calcareous nannofossil-bearing sediment 15cm below the 'Crepidula' band, which could be used to date the strata as 'NP6/7', in the otherwise barren section.

**Sample 1, AG11 - AG16, Sample 2 : LATE PALAEOCENE** : The association of Heliolithus riedelii (abundant) with Towelus tovae, Towelus eminens, Towelus pertusus, and Hornbrookina australis was a clear confirmation of an NP8 zone (Martini, 1971) age for these samples (although Discoaster

FIG. 39.




Lithological section with sample points of the Pegwell Bay area.

Re-drawn from Siesser et al (1987).

Table 17.

| SPECIES | SAMPLE # 1 | AG11 | AG14 | AG16 | 2 | AGE | | STAGE | ZONES " | @ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | T | | |
| Sphenolithus anarrhopus | | | | X | | | | | | |
| Hornibrookina australis | | X | X | X | X | | | H | H | |
| Braarudosphaera bigelowii | | | | X | X | L | P | | . | |
| Prinsius bisulcus | | | X | | | | A | A | | N |
| Neochiastozygus chiastus | X | | | | | | L | | R | |
| Chiasmolithus edentulus | X | X | X | X | X | A | A | N | I | |
| Toweius eminens | X | | X | X | X | | E | | E | P |
| Markalius inversus | | | | X | | | O | E | D | |
| Coccolithus pelagicus | X | X | X | X | X | T | C | | E | |
| Neochiastozygus perfectus | | | | X | | | E | T | L | 8 |
| Toweius pertusus | X | X | X | X | X | | N | | L | |
| Heliolithus riedelii | X | X | X | X | X | E | E | I | I | |
| Placozygus sigmoides | X | X | X | X | X | | | | | |
| Toweius tovae | X | X | X | X | X | | | A | | |
| Fasciculithus tympaniformis | | X | X | X | | | | | | |
| | | | | | | | | N | | |

Table 17. shows the distribution of calcareous nannofossils in the Pegwell Bay samples and their age determination.
" and @ = 'standard' zone defined by Martini (1971).

mohleri and Discoaster nobilis were absent). See Table 17 for species distribution and age determination.

# SYSTEMATIC PALAEONTOLOGY

INTRODUCTION

SYSTEMATIC DESCRIPTIONS

RETICULOFENESTRA : A CRITICAL REVIEW OF

TAXONOMY, STRUCTURE AND EVOLUTION

## WHAT IS A CALCAREOUS NANNOFOSSIL :

Calcareous nannofossils are a diverse, heterogeneous group of morphological forms which are related to, or show gross morphological similarity to, the extant coccolithophores (=coccoliths) which are unicellular marine algae; eucaryotes. Calcareous nannofossils range in size from approximately 2.0-25.0um. Other forms with no clear morphological relationship to the coccolithophores occur as calcareous microfossils within the same size fraction as the coccoliths and are cited as nannoliths.

The most important group are the coccoliths which represent the calcified scales of prymnesiophycean algae (the dominant modern marine phytoplankton), whereas most of the nannoliths are extinct and of uncertain biological affinity.

The biology of calcareous nannoplankton is extensively covered in Haq (1978), Tappan (1980) and most recently in Young (1987).

## PHILOSOPHY OF CLASSIFICATION :

The binary Linnaean nomenclatural system is utilised in calcareous nannofossil classification. Classification is necessarily based upon the morphology of individual parts (the coccoliths) of a complete cell-wall covering. The study of living coccolithophores (Haq, 1978; Tappan, 1980; Young, 1987) has shown that coccoliths are a reliable representation of coccospheres and of biological relationships within a given group. In the majority of cases individual coccoliths reflect the morphology of the complete coccosphere, but exceptions (dimorphism and polymorphism) are known.

There is no general agreement on the higher classification of calcareous nannofossils, consequently many authors arrange genera in alphabetical order for systematic descriptions. This is an unsatisfactory solution to the perplexing problem of classification, but one which should be adopted until a universally acceptable system is developed.

Classifications have been repeatedly attempted in the past, but there has been little discussion of the parameters which determine the suprageneric groupings. Perch-Nielsen (1971) produced a simple 'flow-diagram' to differentiate families on the basis of various (arbitrary ?) morphological attributes. Hay (1977) published a much more detailed scheme, as did Tappan (1980), but in neither case was there discussion of the placement of forms into the suprageneric taxa. Haq (1978) introduced informal epithets for major 'groups' (e.g. coccolithids, pontosphaerids, sphenolithids) of calcareous nannofossils and assigned family names to each. Although this is a workable scheme it is not satisfactory to have informal divisions within a classification.

The higher taxonomic epithets for calcareous nannofossils have been a matter of debate since Hibberd (1976) separated the Prymnesiophyceae from the Chrysophyceae, and used the former in place of the invalid term Haptophyceae. Young (1987) and Rees (pers. comm.) produced schemes based on extant taxa, but the higher divisions appear to apply equally well to fossil forms. Bown (1987) demonstrated that the coccolith rim structure was of fundamental taxonomic importance, as had been deduced by other workers, and central to the evolution of the group by means of analysis of the oldest representatives, from the Triassic and Lower Jurassic. He provided the following definitions (1987, p.12) :

ORDER - Generalised morphology of the rim, e.g. placolith, discolith, etc. and general organisation of the elements within the rim.

FAMILY - Shape and organisation of rim elements together with width and nature of central area.

GENUS - Detailed rim features and general central area structures.

SPECIES - Detailed central area structures.

In this way the suprageneric classification of calcareous nannofossils does not depend on a taxa being collected together with superficially similar forms, but rather on a proven level of morphological similarities and evolutionary links. See also discussion of Noelaerhabdaceae in Chapter 4.

**SYSTEMATIC CLASSIFICATION :**

Systematic descriptions are kept to brief outlines for the most part, as a large number of species was recognised, none are new and most are well-known from the literature.

The name of each species is given, a short synonymy list, its Plate reference for this work, and also its occurrence within the study material and its range. Only species which have been the subject of a special study (e.g. reticulofenestrids) or those for which specific remarks are thought necessary have been described and discussed in greater detail.

The dimensions, negative numbers and locations of figured material are given in the Plate descriptions (Chapter 7).

'Occurrence' is the appearances of the given species within the study material, whilst 'Range' is the stratigraphical extent of the given species according to selected literature sources.

NP and NN zones refer to the zonation of Martini (1971) and subsequent emendation (i.e. Martini and Muller, 1986), CP and CN zones refer to the zonation of Okada and Bukry (1980), and NS zones refer to the zonation defined herein (Chapter 5) for the Tertiary of the North Sea Basin.

| | |
|---|---|
| **DIVISION** | **PRYMNESIOPHYTA** Hibberd, 1976 |
| **CLASS** | **PRYMNESIOPHYCEAE** Hibberd, 1976 |
| **ORDER** | **COCCOLITHALES** Rood et al., 1971 |
| **FAMILY** | **Coccolithaceae** Poche, 1913 |
| **Genus** | Birkelundia Perch-Nielsen, 1971 |

**Type species :** B. arenosa Perch-Nielsen, 1971.

**Species :** Birkelundia staurion (Bramlette and Sullivan) Perch-Nielsen, 1971c.

(Pl.14 Figs.9,10)

**Synonymy :** 1961 Coccolithus staurion Bramlette and Sullivan, p.141, pl.2, figs.5a-b,6a-c.

1971 Birkelundia staurion (Bramlette and Sullivan) Perch-Nielsen, p.11, pl.15, figs.1,3-6; pl.61, figs.16,17.

**Occurrence :** Middle Eocene (NS12-13) of the southern North Sea Basin, and Late Eocene to Early Oligocene of Alabama.

**Range :** Perch-Nielsen (1971c) - Eocene of Texas and California; Bybell (1975) - Middle Eocene (NP15-17) of Alabama.

| | |
|---|---|
| **Genus** | Bramletteius Gartner, 1969b. |

**Type species :** B. serraculoides Gartner, 1969b.

**Species :** Bramletteius serraculoides Gartner, 1969b.

**Synonymy :** 1969 Bramletteius serraculoides Gartner, p.31, pl.1, figs.1-3.

**Occurrence :** Early Oligocene of Alabama.

**Range :** Perch-Nielsen (1985a) - Late Eocene (NP15) to Early Oligocene (NP23).

Genus Calcidiscus Kamptner, 1950.

Type species : C. quadriforatus Kamptner, 1950.

Species : Calcidiscus leptoporus (Murray and Blackman) Loeblich and Tappan, 1978.

(Pl.10 Figs.9,10)

Synonymy : 1898 Coccosphaera leptopora Murray and Blackman, pp.430,493; pl.15, figs.1-7.

1978 Calcidiscus leptoporus (Murray and Blackman) Loeblich and Tappan, p.1391.

Occurrence : Middle and Late Miocene of the central North Sea Basin (NS2-3,6).

Range : Sachs and Skinner (1973) - Miocene to Holocene.

Species : Calcidiscus macintyrei (Bukry and Bramlette) Loeblich and Tappan, 1978.

Synonymy : 1969 Cyclococcolithus macintyrei Bukry and Bramlette, p.132, pl.1, figs.1-3.

1978 Calcidiscus macintyrei (Bukry and Bramlette) Loeblich and Tappan, p.1392.

Occurrence : Middle Miocene of the central North Sea Basin (NS2-3).

Range : Perch-Nielsen (1985a) - Early Miocene (NN4) to Pleistocene (NN19).

Genus Campylosphaera Kamptner, 1963.

Type species : C. bramlettei, Kamptner, 1963.

Species : Campylosphaera dela (Bramlette and Sullivan) Hay and Mohler, 1967.

Synonymy : 1961 Coccolithites delus Bramlette and Sullivan, p.151-152, pl.7, figs.1a-c,2a-b.

1967 Campylosphaera dela (Bramlette and Sullivan) Hay and Mohler, p.1531, pl.198, fig.14.

**Occurrence** : Early Palaeocene of the central North Sea Basin (NS17-18), and Early Eocene (NP12-13) of the Isle of Wight.

**Range** : Hay and Mohler (1967) - Late Palaeocene (D. multiradiatus Zone in Pont Labau, France).

**Genus** *Chiasmolithus* Hay, Mohler and Wade, 1966.

**Type species** : *Tremalithus oamaruensis* Deflandre *in* Deflandre and Fert, 1954.

**Species** : *Chiasmolithus altus* Bukry and Percival, 1971.

(Pl.2 Figs.1-3,7-11,13;Pl.12 Figs.3-6,21)

**Synonymy** : 1971 *Chiasmolithus altus* Bukry and Percival, p.126, pl.2, figs.1-2.

**Occurrence** : Late Oligocene (NS8) of the central North Sea Basin, Late Oligocene (NP24) of the South Atlantic Ocean (ODP 36-329-29-1 and 36-329-30-2) and Late Oligocene (NP24) of the Hatton-Rockall Basin (ODP 12-117-2-3).

**Range** : Bukry and Percival (1971) - Late Eocene to Early Miocene of Blake Plateau; Perch-Nielsen (1985a) - Oligocene (NP22-25).

**Remarks** : A large (10 - 18um), distinctive species of *Chiasmolithus.* Its asymmetrical central area 'cross' distinguishes it from *C. oamaruensis* and it differs from *C. solitus* in having a broader rim and less of an offset between the bars in the central area. This species had a consistent occurrence in the study material, and proved to be of great value for the biostratigraphical sub-division of the Oligocene in the North Sea Basin, in the absence of the established marker species of Martini (1971) and Okada and Bukry (1980).

Species : Chiasmolithus danicus (Brotzen) Van Heck and Perch-Nielsen, 1987.

Synonymy : 1959 Cribrosphaerella danica Brotzen, p.25-26, Fig.9 (invalid ICBN, Art.37.1.).

1987 Chiasmolithus danicus (Brotzen) Van Heck and Perch-Nielsen, p.280, pl.1, figs.11-26,33,34; text-figs.1-4.

Occurrence : Early Palaeocene of the North Sea Basin (NS17-22).

Range : Van Heck and Prins (1987) - Early Palaeocene (lower C. danicus Zone to N. perfectus Zone) of the North Sea Basin.

Remarks : The poor preservation of the study material made it difficult to differentiate this species from C. inconspicuus, a problem which could have repercussions in terms of biostratigraphical accuracy. In specimens where overgrowth was not too severe the central area 'cross' of C. danicus (which varied in structural complexity) was seen to show birefringence in cross-polarised light, whereas the central area 'cross' of C. inconspicuus was seen to be opaque.

Species : Chiasmolithus edentulus Van Heck and Prins, 1987.

(Pl.7 Fig.14; Pl.8 Figs.2,5,9-11; Pl.9 Fig.7; Pl.17 Fig.15)

Synonymy : 1987 Chiasmolithus edentulus Van Heck and Prins, p.288, pl.1, figs.13,14; text-fig.5.

Occurrence : Early Palaeocene of the North Sea Basin (NS16-18) and Late Palaeocene (NP8) of the Pegwell Bay section, Kent.

Range : Van Heck and Prins (1987) - Early Palaeocene (middle C. inconspicuus Zone to N. perfectus Zone) of the North Sea Basin.

Remarks : The largest of the Palaeocene representatives of Chiasmolithus in the study material, the central area cross structure has two straight, and two sigmoid bars which show weak birefringence in cross-polarised light. C. edentulus has been recorded as C. bidens in the past, but lacks 'tooth-like' projections from the wall. A very useful marker species for the Early Palaeocene of the North Sea Basin as it can be recognised even in the poorest preserved samples.

Species : Chiasmolithus edwardsii (Romein) Van Heck and Prins, 1987.

Synonymy : 1979 Cruciplacolithus edwardsii Romein, p.101, pl.2, figs.7,8; pl.9, figs.9,10.

1987 Chiasmolithus edwardsii (Romein) Van Heck and Prins, p.288-289, text-fig.6.

Occurrence : Early Palaeocene of the North Sea Basin (NS18-20).

Range : Van Heck and Prins (1987) - Early Palaeocene (C. asymmetricus Zone to C. inconspicuus Zone) of the North Sea Basin.

Species : Chiasmolithus expansus (Bramlette, and Sullivan) Gartner, 1970.

(Pl.6 Figs.8,11; Pl.15 Figs.9,10)

Synonymy : 1961 Coccolithus expansus Bramlette and Sullivan, p.139-140, pl.1, fig.4a-d.

1970 Chiasmolithus expansus (Bramlette and Sullivan) Gartner, p.943, pl.11, fig.1,2a-b.

Occurrence : Middle Eocene (NS13) of the southern North Sea Basin, Middle to Late Eocene (NP15-18) of Hampden Beach, New Zealand, and Middle Eocene (NP14-16) of the Isle of Wight.

Range : Sherwood (1974) - Early to Middle Eocene of Texas; Perch-Nielsen (1985a) - NP14-16.

Species : Chiasmolithus grandis (Bramlette and Riedel) Gartner, 1970.

(Pl.D. Figs.3,4.)

Synonymy : 1954 Coccolithus grandis Bramlette and Riedel, p.391-392, pl.38, figs.1a-b.

1970 Chiasmolithus grandis (Bramlette and Riedel) Gartner, p.944, pl.11, figs.3; pl.14, figs.1-3.

**Occurrence** : Middle Eocene of the southern North Sea Basin (NS13).

**Range** : Gartner (1970) - Early to Middle Eocene; Perch-Nielsen (1985a) - NP11-17.

**Species** : Chiasmolithus inconspicuus Van Heck and Prins, 1987.

(Pl.8 Fig.8; Pl.9 Figs.5,6; Pl.Pl.17 Fig.19)

**Synonymy** : 1987 Chiasmolithus inconspicuus Van Heck and Prins, p.289, pl.1, figs.11,12; text-fig.7.

**Occurrence** : Early Palaeocene of the North Sea Basin (NS16-18).

**Range** : Van Heck and Prins (1987) - Early Palaeocene (N. saepes Zone to N. perfectus Zone) of the North Sea Basin.

**Remarks** : As mentioned above this species is very similar (structurally) to C. danicus, but can be differentiated by the non-birefringent nature of its central area 'cross' in cross-polarised light. C. inconspicuus proved quite a good marker species for the middle part of the Early Palaeocene of the North Sea Basin, despite the problems associated with poorly preserved assemblages.

**Species** : Chiasmolithus nitidus Perch-Nielsen, 1971c.

(Pl.13 Figs.9,10)

**Synonymy** : 1971 Chiasmolithus nitidus Perch-Nielsen, p.20, pl.13, figs.5,6; pl.60, figs.13,14.

**Occurrence** : Middle to Late Eocene of the southern North Sea Basin (NS11-13).

**Range** : Perch-Nielsen (1971c) - Late Eocene of Denmark; Perch-Nielsen (1985a) - NP15-16.

Species : Chiasmolithus oamaruensis (Deflandre) Hay, Mohler and Wade, 1966.

(Pl.C. Figs.4,8,12; Pl.4 Fig.4; Pl.5 Fig.12; Pl.6 Figs.7,9,10; Pl.13 Figs.15,16; Pl.14 Fig.23)

Synonymy : 1954 Tremalithus oamaruensis Deflandre in Deflandre and Fert, p.154, pl.11, fig.22, text-figs.72-74.

1965 Coccolithus oamaruensis (Deflandre) Levin, p.265-266, pl.41, fig.3.

1966 Chiasmolithus oamaruensis (Deflandre) Hay, Mohler and Wade, p.388-389, pl.7, fig.1.

Occurrence : Middle Eocene of the southern North Sea Basin (NS12), Late Eocene (NP19) of Hampden Beach, New Zealand, and Late Eocene (NP20) of William's Bluff, New Zealand.

Range : Hay, Mohler and Wade (1966) - Late Eocene of north-west Caucasus; Gartner (1970) - Late Eocene to Early Oligocene; Perch-Nielsen (1985a) - NP18-22.

Remarks : A very large, distinctive species of Chiasmolithus, which is distinguished by its acutely angled, symmetrically placed central area 'cross'. C. oamaruensis was not a consistent member of the assemblages recovered from the North Sea Basin , but this is thought to be a result of sampling, rather than the true distribution of the species. It is envisaged that further investigation of Late Eocene material from the North Sea Basin will establish the biostratigraphical value of this species.

Species : Chiasmolithus solitus (Bramlette and Sullivan) Locker, 1968.

(Pl.A. Figs.13,17,21; Pl.5 Fig.1,2; Pl.15 Figs 13,14)

Synonymy : 1961 Coccolithus solitus Bramlette and Sullivan, p.140-141, pl.2, fig.4a-c.

1988 Chiasmolithus solitus (Bramlette and Sullivan) Locker, p.222, pl.1, figs.5,6.

**Occurrence** : Middle Eocene of the southern North Sea Basin (NS12-14), and Middle to Late Eocene (NP15-18) of Hampden Beach New Zealand.

**Range** : Bramlette and Sullivan (1961) - Early to Middle Eocene of Texas; Gartner (1970) - Early to Middle Eocene; Perch-Nielsen (1985a) - NP10-16.

**Species** : Chiasmolithus titus Gartner, 1970.

(Pl.13 Figs.19,20)

**Synonymy** : 1970 Chiasmolithus titus Gartner, p.945-946, pl.17, figs.1-3.

**Occurrence** : Middle Eocene of the southern North Sea Basin (NS12-13), and Early Oligocene (NP21) of Alabama.

**Range** : Gartner (1970) - Middle to Late Eocene of Alabama; Perch-Nielsen (1985a) - Middle Eocene to Early Oligocene (NP15-21).

**Genus** Coccolithus Schwarz, 1894

**Type species** : Coccosphaera pelagica Wallich, 1877.

**Species** : Coccolithus pelagicus (Wallich) Schiller, 1930.

(Pl.D. Figs.9,10; Pl.2 Fig.6)

**Synonymy** : 1877 Coccosphaera pelagica Wallich, p.348, pl.17, figs.1,3-7,10.

1927 Coccolithophora pelagica (Wallich) Lohmann - Tan Sin Hok, p.111-112, pl.3, figs.1,2.

1930 Coccolithus pelagicus (Wallich) Schiller, p.246, fig.123.

**Occurrence** : Early Eocene to Miocene of the North Sea Basin (NS2-15), and throughout most of the other sections studied.

**Range** : Perch-Nielsen (1985a) - Palaeocene to Recent.

**Genus** Coronocyclus Hay, Mohler and Wade, 1966

**Type species :** C. serratus Hay, Mohler and Wade, 1966.

**Species :** Coronocyclus nitescens (Kamptner) Bramlette and Wilcoxon, 1967.

**Synonymy :** 1963 Umbilicosphaera nitescens Kamptner, p.187-188, pl.1, fig.5; text-fig.37.

1967 Coronocyclus nitescens (Kamptner) Bramlette and Wilcoxon, p.103, pl.1, fig.4; pl.5, figs.7-8.

**Occurrence :** Late Eocene to Miocene of the North Sea Basin (NS3,8,10-11).

**Range :** Bramlette and Wilcoxon (1967) - Oligocene to Middle Miocene of Trinidad.

**Genus** Cruciplacolithus Hay and Mohler in Hay et al., 1967

**Type species :** Heliorthus tenuis Stradner, 1961.

**Species :** Cruciplacolithus asymmetricus Van Heck and Prins, 1987.

**Synonymy :** 1987 Cruciplacolithus asymmetricus Van Heck and Prins, p.289-290, pl.1, figs.5-8; text-figs.8a,b.

**Occurrence :** Early Palaeocene of the North Sea Basin (NS17-18).

**Range :** Van Heck and Prins (1987) - Early Palaeocene (C. asymmetricus Zone to C. inconspicuus Zone) of the North Sea Basin.

**Species :** Cruciplacolithus intermedius Van Heck and Prins, 1987.

**Synonymy :** 1987 Cruciplacolithus intermedius Van Heck and Prins, p.290, pl.1, figs.1-3; text-fig.9.

**Occurrence :** Early Palaeocene of the North Sea Basin (NS16-22).

**Range :** Van Heck and Prins (1987) - Early Palaeocene (C. asymmetricus Zone to C. inconspicuus Zone) of the North Sea Basin.

Species : Cruciplacolithus primus Perch-Nielsen, 1977.

Synonymy : 1977 Cruciplacolithus primus Perch-Nielsen, p.746, pl.17, figs.7,8; pl.50, figs.11,12.

Occurrence : Early Palaeocene of the North Sea Basin (NS17-18,22-23).

Range : Van Heck and Prins (1987) - Early Palaeocene (B. sparsus Zone to N. perfectus Zone) of the North Sea Basin; Perch-Nielsen (1985a) - NP1-4.

Species : Cruciplacolithus quader Roth, 1970.

Synonymy : 1970 Cruciplacolithus quader Roth, p.845, pl.3, fig.1.

Occurrence : Middle Eocene of the southern North Sea Basin (NS13).

Range : Roth (1970) - Middle Oligocene of Blake Plateau.

Species : Cruciplacolithus tenuis (Stradner) Hay and Mohler, 1967.

(Pl.B. Figs.15,19,23; Pl.17 Figs.17,18)

Synonymy : 1961 Heliorthus tenuis Stradner, p.84, text-figs.64,65.

1967 Cruciplacolithus tenuis (Stradner) Hay and Mohler, p.1527-1528, pl.196, figs.29-31; pl.198, figs.1,17.

Occurrence : Early Palaeocene of the North Sea Basin (NS16-22).

Range : Van Heck and Prins (1987) - Early Palaeocene (C. asymmetricus Zone to N. perfectus Zone) of the North Sea Basin; Perch-Nielsen (1985a) - NP2-9.

Genus Cyclagelosphaera Noël, 1965

Type species : C. margerelii Noël, 1965.

Species : Cyclagelosphaera alta Perch-Nielsen, 1979.

Synonymy : 1979 Cyclagelosphaera alta Perch-Nielsen, p.125, pl.3, fig.7.

Occurrence : Early Palaeocene of the central North Sea Basin (NS17-18).

Range : Perch-Nielsen (1985a) - Early Palaeocene.

**Species** : Cyclagelosphaera margerelii Noël, 1965.

**Synonymy** : 1965 Cyclagelosphaera margerelii Noël, p.130-131, pl.17, figs.44-46; pl.18, figs.1,2; pl.20, figs.2-4.

**Occurrence** : Middle Eocene of 49/10-1 (NS13).

**Range** : Perch-Nielsen (1985a) - Cretaceous to Early Palaeocene.

**Species** : Cyclagelosphaera reinhardtii (Perch-Nielsen) Romein, 1977.

**Synonymy** : 1968 Markalius reinhardtii Perch-Nielsen, p.76, pl.23, figs.6-8; text-fig.38.

**Occurrence** : Early Palaeocene of the North Sea Basin (NS1,20).

**Range** : Perch-Nielsen (1985a) - Cretaceous to Early Palaeocene.

**Genus** Ericsonia Black, 1964

**Type species** : E. occidentalis Black, 1964.

**Species** : Ericsonia cava (Hay and Mohler) Perch-Nielsen, 1969.

**Synonymy** : 1967 Coccolithus cavus Hay and Mohler, p.1524-1525, pl.196, figs.1-3; pl.197, figs.5,7,10,12.

1969 Ericsonia cava (Hay and Mohler) Perch-Nielsen, p.61, pl.2, figs.7,8.

**Occurrence** : Early Palaeocene of the North Sea Basin (NS17-22).

**Range** : Hay and Mohler (1967) - Palaeocene (C. tenuis Zone to D. multiradiatus Zone) of Pont Labau, France; Romein (1979) - C. primus Zone to E. macellus Zone in Scandinavia and Spain.

**Species** : Ericsonia fenestrata (Deflandre and Fert) Stradner in Stradner and Edwards, 1968.

(Pl.D. Figs.13,14; Pl.15 Fig.21)

**Synonymy** : 1954 Discolithus fenestratus Deflandre and Fert, p.25, pl.11, fig.25; text-figs.18,52.

1968 Ericsonia fenestrata Stradner in Stradner and Edwards, p.18, pl.10, figs.1-4; pl.11, figs.1-7.

**Occurrence** : Middle Eocene of the North Sea Basin (NS12-13), Late Eocene of the Isle of Wight (NP17), and Middle to Late Eocene of Hampden Beach, New Zealand (NP15-18).

**Range** : Stradner and Edwards (1968) - late Middle Eocene to Late Oligocene of New Zealand; Perch-Nielsen (1985a) - Middle Eocene to Early Oligocene.

**Species** : Ericsonia formosa (Kamptner) Romein, 1979.

(Pl.A. Figs.3,7,11; Pl.4 Fig.10; Pl.12 Figs.17,18; Pl.14 Figs.7,8)

**Synonymy** : 1963 Cyclococcolithus formosus Kamptner, p.163, pl.2, fig.8.

1964 Coccolithus lusitanicus Black, p.312, pl.50, figs.1,2.

1971 Cyclococcolithina formosa (Kamptner) Gartner, p.109.

1979 Ericsonia formosa (Kamptner) Romein, p.111.

**Occurrence** : Early Eocene to Early Oligocene of the North Sea Basin (NS10-14), Late Eocene (NP20) of William's Bluff, New Zealand, Middle to Late Eocene (NP15-19) of Hampden Beach, New Zealand, Late Eocene to Early Oligocene (NP20-21) of Alabama, and Middle Eocene (NP14-16) of the Isle of Wight.

**Range** : Romein (1979) - Early to Middle Eocene (T. contortus Zone to N. fulgens Zone) of Spain; Perch-Nielsen (1985a) - NP12-21.

**Species** : Ericsonia obruta Perch-Nielsen, 1971c.

(Pl.12 Figs.19,20)

**Synonymy** : 1971 Ericsonia obruta Perch-Nielsen, p.14, pl.4, figs.4-7; pl.8, figs.5,6; pl.61, figs.10,11

**Occurrence :** Middle to Late Eocene of the southern North Sea Basin (NS11-14), and Early Oligocene (NP21) of Alabama.

**Range :** Perch-Nielsen (1971c) - Middle Eocene of Denmark.

**Species :** Ericsonia robusta (Bramlette and Sullivan) Perch-Nielsen, 1977.

**Synonymy :** 1961 Cyclolithus ? robustus Bramlette and Sullivan, p.141, pl.2, fig.7.

1977 Ericsonia cf. E. robusta (Bramlette and Sullivan) Perch-Nielsen, partim, pl.16, figs.1,4,5, non pl.16, fig.6.

non 1977 Ericsonia robusta (Bramlette and Sullivan) Perch-Nielsen, p.774, pl.16, figs.2,7.

**Occurrence :** Early Palaeocene of the central North Sea Basin (NS18).

**Range :** Bramlette and Sullivan (1961) - Palaeocene of California; Romein (1979) - Late Palaeocene of Spain and Israel; Perch-Nielsen (1985a) - Early to Late Palaeocene.

**Species :** Ericsonia subdisticha (Roth and Hay in Hay et al.) Roth in Baumann and Roth, 1969.

(Pl.D. Figs.23,24; Pl.6 Fig.4; Pl.13 Figs.3,4)

**Synonymy :** 1967 Ellipsolithus subdistichus Roth and Hay in Hay et al., p.446-447, pl.6, fig.7.

1969 Ericsonia subdisticha (Roth and Hay in Hay et al.) Roth in Baumann and Roth, p.319.

**Occurrence :** Middle Eocene to Early Oligocene of the North Sea Basin (NS10-14), Late Eocene (NP20) of William's Bluff, New Zealand, Early Oligocene (NP21) of JOIDES Hole 5, and Late Eocene to Early Oligocene (NP20-21) of Alabama.

**Range :** Roth and Hay in Hay et al. (1967) - Early Oligocene of Blake Plateau;

Roth (1970) - Early Oligocene (E. subdisticha Zone) of Alabama, Monte Cagnero, Italy and Helmstedt in northern Germany. Also in the Late Eocene; Perch-Nielsen (1985a) - Late Eocene to Early Oligocene (NP20-21).

Species : Ericsonia subpertusa Hay and Mohler, 1967.

Synonymy : 1967 Ericsonia subpertusa Hay and Mohler, p.1531, pl.198, figs.11,15,18; pl.199, figs.1-3.

Occurrence : Early Palaeocene of the North Sea Basin (NS16-18,20-22).

Range : Hay and Mohler (1967) - Palaeocene (upper C. tenuis Zone to D. multiradiatus Zone) of Pont Labau, France; Romein (1979) - Early to Late Palaeocene of Spain, Israel, and Scandinavia.

Genus Ilselithina Stradner in Stradner and Adamiker, 1966

Type species : Ilselithina iris Stradner in Stradner and Adamiker, 1966.

Species : Ilselithina fusa Roth, 1970.

Synonymy : 1970 Ilselithina fusa Roth, p.856, pl.7, figs.2,3.

Occurrence : Early Oligocene (NP21) of Alabama.

Range : Roth (1970) - Early Oligocene (E. subdisticha Zone to C. margaritae Zone) of Blake Plateau, C. margaritae Zone of Barbados, Early Oligocene (E. subdisticha Zone to R. laevis Zone) of Alabama, and other Early Oligocene occurrences in the Silberberg Beds, Helmstedt, the Clay Pit Alversdorf, near Helmstedt, and the Boom Clay in Belgium.

Genus Markalius Bramlette and Martini, 1964

Type species : Markalius inversus (Deflandre) Bramlette and Martini, 1964

Species : Markalius inversus (Deflandre in Deflandre and Fert) Bramlette and Martini, 1964.

**Synonymy :** 1964 Markalius inversus (Deflandre in Deflandre and Fert) Bramlette and Martini, p.302, pl.2, figs.4-9; pl.7, fig.2a-b.

See Grün and Allemann (1975) for further references.

**Occurrence :** Early Palaeocene to Late Eocene (NS11-20) of the North Sea Basin, Late Eocene to Early Oligocene (NP20-21) of Alabama, Middle Eocene (NP14-16) of the Isle of Wight, Late Oligocene (NP24) of the South Atlantic Ocean (ODP-36-329-30-2, 132-133cm), and Late Palaeocene (NP8) of Pegwell Bay, Kent.

**Range :** Perch-Nielsen (1985a) - Cretaceous to Eocene.

**Genus** Pedinocyclus Bukry and Bramlette, 1971

**Type species :** P. larvalis (Bukry and Bramlette) Loeblich and Tappan, 1973.

**Species :** Pedinocyclus larvalis (Bukry and Bramlette) Loeblich and Tappan, 1973.

**Synonymy :** 1969 Leptodiscus larvalis Bukry and Bramlette, p.134-136, pl.2, figs.8-11.

1971 Pedinocyclus larvalis (Bukry and Bramlette) Gartner, p.105. (Inv. ICBN Art. 33.4).

1973 Pedinocyclus larvalis (Bukry and Bramlette) Loeblich and Tappan, p.738.

**Occurrence :** Early Oligocene (NP21) of Alabama.

**Range :** Perch-Nielsen (1985a) - Late Eocene to Early Oligocene.

**Genus** Pyrocyclus Hay and Towe, 1962

**Type species :** P. inversus Hay and Towe, 1962.

**Species :** Pyrocyclus hermosus Roth and Hay in Hay et al., 1967.

**Synonymy :** 1967 Pyrocyclus hermosus Roth and Hay in Hay et al., p.448, pl.6, figs.10-12.

**Occurrence :** Late Eocene and Early Miocene of the North Sea Basin (NS5,11), and Late Oligocene (NP24) of JOIDES Hole 5.

Range : Backman (1980) - Miocene to Pliocene of the Hatton-Rockall Basin.

Species : Pyrocyclus orangensis (Bukry) Backman, 1980.

Synonymy : 1971 Coccolithus ? orangensis Bukry, p.312, pl.2, figs.10,11.

1980 Pyrocyclus orangensis (Bukry) Backman, p.56, pl.3, figs.6,7.

Occurrence : Late Oligocene to Early Miocene of the central North Sea Basin (NS5-6,11).

Range : Backman (1980) - Miocene of the Hatton-Rockall Basin.

FAMILY Noelaerhabdaceae Jerković, 1970

Genus Cyclicargolithus Bukry, 1971

Type species : Coccolithus floridanus Roth and Hay in Hay et al., 1967

Species : Cyclicargolithus abisectus (Müller) Wise, 1973.

(Pl.2 Figs.4,5,9,12,14,15; Pl.11 Fig.21)

Synonymy : 1970 Coccolithus abisectus Müller, p.112, pl.9, figs.1,2.

1971 Dictyococcites abisectus (Müller) Bukry and Percival, p.127, pl.2, figs.9-11.

1972 Reticulofenestra abisecta (Müller) Roth and Thierstein, p.436.

1973 Cyclicargolithus abisectus (Müller) Wise, p.594.

Occurrence : Late Oligocene to Middle Miocene of the North Sea Basin (NS3-8), Late Oligocene (NP24) of the South Atlantic Ocean (ODP-36-329-29-1, 138-139cm), and Late Oligocene (NP24) of the Hatton-Rockall Basin (ODP-12-117-2-3, 147-148cm).

Range : Perch-Nielsen (1985a) - Late Oligocene to Early Miocene (NP24-NN2).

Remarks : A large species (6 -10um) of Cyclicargolithus, which is structurally very similar to C. floridanus (see discussion at end of Chapter 4). It has a near circular outline, with a small circular opening in the central area. There is no grill or net-like structure in this central pore. The broad distal rim is composed of 40-60 radial, or slightly inclined elements which show high birefringence and distinct extinction lines in cross-polarised light. This species had a restricted occurrence in the North Sea Basin (Early Miocene to Late Oligocene) and was particularly effective in the sub-division of the Late Oligocene.

**Species :** Cyclicargolithus floridanus (Roth and Hay in Hay et al.) Bukry, 1971a.

(Pl.3 Fig.4,7; Pl.11 Figs.17,18)

**Synonymy :** 1967 Coccolithus floridanus Roth and Hay in Hay et al., p.445, pl.6, figs.1-4.

1967 Cyclococcolithus neogammation Bramlette and Wilcoxon, p.104, pl.1, figs.1-3; pl.4, figs.3-5.

1970 Cyclococcolithus floridanus (Roth and Hay in Hay et al.) Roth, p.854, pl.5, fig.6.

1971 Cyclicargolithus floridanus (Roth and Hay in Hay et al.) Bukry, p.312.

1984 Reticulofenestra floridana (Roth and Hay in Hay et al.) Theodoridis, p.85, pl.5, fig.8.

**Occurrence :** Middle Eocene to Middle Miocene of the North Sea Basin (NS2-13), Middle Eocene to Early Oligocene of many other sections studied.

**Range :** Bramlette and Wilcoxon (1967) - Oligocene to Middle Miocene of Trinidad; Muller (1970) - Oligocene to Early Miocene of Germany; Roth (1973) - Oligocene to Miocene; Perch-Nielsen (1985a) - Late Eocene to Middle Miocene (NP20-NN6).

**Remarks :** A smaller, more sub-circular species than C. abisectus, but nevertheless a very similar one in terms of structure. C. floridanus is composed of 40+ elements which may be radial or slightly inclined and has a small central pore which is free from any kind of grilll or net-like structure. In cross-polarised light the shields show high birefringence and distinctive extinction lines. This species occurs throughout most of the wells studied, thus it does not have specific biostratigraphical applicability, however, its FDO in the Middle Miocene is a useful datum.

Genus Hornibrookina Edwards, 1973

Type species : H. teuriensis Edwards, 1973

Species : Hornibrookina australis Edwards and Perch-Nielsen, 1975.

Synonymy : 1975 Hornibrookina australis Edwards and Perch-Nielsen, p.485, pl.2, figs.1-3,6,9,12; pl.5, figs.6,9,12.

Occurrence : Late Palaeocene (NP8) of Pegwell Bay, Kent.

Range : Perch-Nielsen (1985a) - Palaeocene (NP6-10) of the North Atlantic.

Genus Prinsius Hay and Mohler, 1967

Type species : Coccolithus bisulcus Stradner in Gohrbandt, 1963

Species : Prinsius bisulcus (Stradner in Gohrbandt) Hay and Mohler, 1967.

(Pl.17 Fig.16)

Synonymy : 1963 Coccolithus bisulcus Stradner in Gohrbandt, p.72, pl.8, figs.3-6; text-fig.3a,b.

1967 Prinsius bisulcus (Stradner in Gohrbandt) Hay and Mohler, p.1529-1530, pl.196, figs.10-13; pl.197, fig.6

Occurrence : Early Palaeocene of the North Sea Basin (NS17-18), and Late Palaeocene (NP8) of Pegwell Bay, Kent.

Range : Romein (1979) - Palaeocene (E. macellus Zone to D. multiradiatus Zone) of Spain; Perch-Nielsen (1985a) - Palaeocene (NP4-9).

**Species** : Prinsius dimorphosus (Perch-Nielsen) Perch-Nielsen, 1977.

(Pl.9 Figs.4,15; Pl.17 Figs.21,22)

**Synonymy** : 1969 Biscutum ? dimorphosum Perch-Nielsen, p.318, pl.32, figs.1-3a,4; text-fig.1.

1977 Prinsius dimorphosus (Perch-Nielsen) Perch-Nielsen, p.794, pl.30, figs.10-13.

**Occurrence** : Early Palaeocene of the North Sea Basin (NS16-23).

**Range** : Romein (1979) - Early Palaeocene (P. dimorphosus Zone to E. macellus Zone) of Israel and Scandinavia; Perch-Nielsen (1985a) - Early Palaeocene (NP2-4).

**Remarks** : An extremely small species of Prinsius, which may be circular to elliptical in outline. It is constructed of radially disposed elements in the proximal and distal shields and has a tube cycle of 'blocky' elements around the margin of the central opening. The central area contains a simply constructed grill. This species was extremely common in the sample material as a 'background' member of the assemblage. It differs from other species of Prinsius by its small size (2 - 3um) and its extremely simple construction. In cross-polarised light the rim remains dark, but the tube cycle shows high birefringence.

**Species** : Prinsius martinii (Perch-Nielsen) Haq, 1971.

**Synonymy** : 1969 Ericsonia ? martinii Perch-Nielsen, p.324, pl.32, figs.3b,5-7; text-fig.2.

1971 Prinsius martinii (Perch-Nielsen) Haq, partim, p.18, pl.5, figs.2,3,5,10; non pl.5, fig.1.

**Occurrence** : Early Palaeocene of the North Sea Basin (NS16-18).

**Range** : Romein (1979) - Palaeocene (C. tenuis Zone to D. mohleri Zone) of Spain and Scandinavia; Perch-Nielsen (1985a) - Palaeocene (NP3-6)

Species : Prinsius tenuiculus (Okada and Thierstein) Perch-Nielsen, 1984.

Synonymy : 1979 Biscutum ? tenuiculum Okada and Thierstein, p.521-522, pl.9, fig.5.

1984 Prinsius tenuiculum (Okada and Thierstein) Perch-Nielsen, p.42.

Occurrence : Early Palaeocene of the North Sea Basin (NS18,20-23).

Range : Perch-Nielsen (1985a) - Early Palaeocene (NP3-4).

Genus Reticulofenestra (Hay, Mohler and Wade) emend.

Type species : Reticulofenestra umbilicus (Levin) Martini and Ritzkowski, 1968

See Chapter 6 for details of the systematic classification of all Reticulofenestra species, and a discussion of their taxonomy, structure and evolution.

Genus Toweius Hay and Mohler, 1967

Type species : Toweius craticulus Hay and Mohler, 1967.

Species : Toweius crassus (Bramlette and Sullivan) Perch-Nielsen, 1984.

Synonymy : 1961 Coccolithus crassus Bramlette and Sullivan, p.139, pl.1, fig.4a-d.

1984 Toweius ? crassus (Bramlette and Sullivan) Perch-Nielsen, p.42.

Occurrence : Early Eocene of the North Sea Basin (NS15), and Early Eocene (NP11) of the London Clay Formation, North London area.

Range : Perch-Nielsen (1985a) - Early to Middle Eocene (NP12-15).

Species : Toweius eminens (Bramlette and Sullivan) Gartner, 1971a.

(Pl.8 Fig.4,14)

Synonymy : 1961 Coccolithus eminens Bramlette and Sullivan, p.139, pl.1, fig.3a-d.

1967 Cruciplacolithus eminens (Bramlette and Sullivan) Hay and

Mohler, p.1527, pl.196, figs.26-28; non pl.198, figs.9,10.

1971 Towelus eminens (Bramlette and Sullivan) Gartner, p.114-115, pl.5, figs.4-6.

**Occurrence** : Early Eocene of 14/29-1 (NS18), and Late Palaeocene (NP8) of Pegwell Bay, Kent.

**Range** : Bramlette and Sullivan (1961) - Palaeocene of California, Alabama and the type Thanetian of England; Romein (1979) - Late Palaeocene to Early Eocene (D. mohleri Zone to T. contortus Zone) of Spain and Israel; Gartner (1971a) - Late Palaeocene to Early Eocene (D. gemmeus Zone to M. contortus Zone) of Blake Plateau.

**Remarks** : A relatively large (7 - 9um) species of Towelus which can be distinguished by the fact that it has only 4 symmetrically displaced pores in the distal surface of the tube cycle. The bars which separate these pores are projections from the inner tube cycle. The outer tube cycle was well developed in all specimens seen in the study material. T. eminens was common in samples of late Early Palaeocene and Late Palaeocene age and could be used in association with other marker species to sub-divide this interval.

**Species** : Towelus gammation (Bramlette and Sullivan) Romein, 1979.

**Synonymy** : 1961 Coccolithus gammation Bramlette and Sullivan, p.152, pl.7, figs.7,14.

1964 Cyclococcolithus gammation (Bramlette and Sullivan) Sullivan, p.181, pl.3, fig.7.

1979 Towelus gammation (Bramlette and Sullivan) Romein, p.126, pl.4, figs.4,5

**Range** : Romein (1979) - Early Eocene (D. binodosus Zone to D. sublodoensis Zone) of Israel; Perch-Nielsen (1985a) - Early to Middle Eocene (NP11-15).

**Species** : Toweius magnicrassus (Bukry) Romein, 1979.

**Synonymy** : 1971 Coccolithus magnicrassus Bukry, p.309, pl.2, figs.1-5.

1979 Toweius magnicrassus (Bukry) Romein, p.126, pl.4, figs.2,3.

**Occurrence** : Early Eocene of the North Sea Basin (NS15).

**Range** : Bukry (1971a) - Early Eocene of the North Pacific, North Atlantic Oceans, and the Donzacq Marl of France; Romein (1979) - Early Eocene of Spain and Israel; Perch-Nielsen (1985a) - Early Eocene (NP11-14).

**Species** : Toweius occultatus (Locker) Perch-Nielsen, 1971c.

(Pl.17 Figs.3,7)

**Synonymy** : 1967 Coccolithus occultatus Locker, p.764-765, pl.1, fig.5; pl.2, figs.9,10.

1971 Toweius occultatus (Locker) Perch-Nielsen, p.32-33, pl.17, figs.1,2,4,7; pl.18, fig.6.

**Occurrence** : Early Eocene of the North Sea Basin (NS15), and Early Eocene (NP12 ?) of the Isle of Wight.

**Range** : Perch-Nielsen (1971c) - Early Eocene of Denmark; Romein (1979) - Early Eocene (T. contortus Zone to D. lodoensis Zone) of Spain and Israel; Perch-Nielsen (1985a) - Early Eocene (NP12).

**Remarks** : Elliptical in outline with two longitudinal 'teeth' projecting from the inner tube cycle into the distally open central area. The distal shield is composed of 40-60 elements. This species was very distinctive, and very useful biostratigraphically, in the Early Eocene of the North Sea Basin, and the London Clay Formation of the comparative material.

**Species** : Toweius pertusus (Sullivan) Romein, 1979.

**Synonymy** : 1965 Coccolithus pertusus Sullivan, p.32, pl.3, figs.5,6.

1967 Towelus craticulus Hay and Mohler, p.1530, pl.196, figs.7-9; pl.197, figs.2,3.

1979 Towelus pertusus (Sullivan) Romein, p.124-125, pl.3, fig.9.

**Occurrence :** Early Palaeocene to early Eocene of the North Sea Basin (NS15-18), Early Eocene (NP11-12) of the London Clay Formation, North London area, Early Eocene (NP11-12) of the Isle of Wight, and Late Palaeocene (NP8) of Pegwell Bay, Kent.

**Range :** Romein (1979) - Late Palaeocene to Early Eocene (F. tympaniformis Zone to T. orthostylus Zone) of Spain; Perch-Nielsen (1985a) - Late Palaeocene to Early Eocene (NP6-13).

**Species :** Towelus tovae Perch-Nielsen, 1971b.

(Pl.A. Figs.15,19,23; Pl.8 Fig.12; Pl.9 Figs.8,10; Pl.17 Figs.13,14)

**Synonymy :** 1971 Towelus tovae Perch-Nielsen, p.359-360, pl.13, figs.1-3,5; pl.14, figs.8,9.

**Occurrence :** Early Palaeocene of the North Sea Basin (NS16-18), and Late Palaeocene (NP8) of Pegwell Bay, Kent.

**Range :** Perch-Nielsen (1985a) - Late Palaeocene (NP9).

**ORDER** **DISCOASTERALES** Hay, 1977

**FAMILY** **Braarudosphaeraceae** Deflandre, 1947

**Genus** Braarudosphaera Deflandre, 1947

**Type species :** Pontosphaera bigelowii Deflandre, 1947.

**Species :** Braarudosphaera bigelowii (Gran and Braarud) Deflandre, 1947.

(Pl.1 Fig.8; Pl.3 Fig.9)

**Synonymy :** 1935 Pontosphaera bigelowii Gran and Braarud, p.338, fig.67.

1947 Braarudosphaera bigelowii (Gran and Braarud) Deflandre, p.439, text-figs.1-5.

See Haq (1971) for further references.

**Occurrence** : Palaeocene to Pliocene of the North Sea Basin (NS1-18), and throughout the Tertiary of many of the other study sections.

**Range** : Perch-Nielsen (1985a) - Palaeocene to Recent.

**Species** : Braarudosphaera discula Bramlette and Riedel, 1954

**Synonymy** : 1954 Braarudosphaera discula Bramlette and Riedel, p.394, pl.38, fig.7.

1960 Braarudosphaera discula Bramlette and Riedel - Bramlette and Sullivan, p.153, pl.8, figs.6a,b,7.

**Occurrence** : Early Palaeocene of 29/10-1 (NS18).

**Range** : Bramlette and Riedel (1954) - lower Middle Eocene of Pacific Ocean; Sullivan (1964) - Palaeocene of California.

**Genus** Micrantholithus Deflandre, 1954

**Type species** : M. flos Deflandre, 1950.

**Species** : Micrantholithus aequalis Sullivan, 1964.

(Pl.D. Figs.15,16; Pl.1 Fig.15; Pl.10 Figs.17,18)

**Synonymy** : 1964 Micrantholithus aequalis Sullivan, p.188, pl.9, fig.6a,b.

**Occurrence** : Early Oligocene to Miocene of the central North Sea Basin (NS3,7,10).

**Range** : Sullivan (1964) - Palaeocene and Early Eocene of California.

**Species** : Micrantholithus inaequalis Martini, 1961.

**Synonymy** : 1961 Micrantholithus inaequalis Martini, p.125.

**Occurrence** : Late Eocene and Miocene of the central North Sea Basin

(NS3,6,7,11).

**Range :** Martini (1961) - Eocene of Germany.

**Species :** Micrantholithus truncus Bramlette and Sullivan, 1961.

(Pl.10 Figs.19,20)

**Synonymy :** 1961 Micrantholithus truncus Bramlette and Sullivan, p.155-156, pl.9, fig.9a,b.

**Occurrence :** Middle Eocene and Miocene of the North Sea Basin (NS3,7,12).

**Range :** Bramlette and Sullivan (1961) - Palaeocene of California.

**Species :** Micrantholithus vesper Deflandre, 1950.

(Pl.11 Figs.9,10)

**Synonymy :** 1950 Micrantholithus vesper Deflandre, p.1157, text-figs.5-7.

**Occurrence :** Middle to Late Eocene of the North Sea Basin (NS11-13), and Middle Eocene (NP14-16) of the Isle of Wight.

**Range :** Bramlette and Sullivan (1961) - Early to Middle Eocene of California, Middle Eocene (Lutetian) of Donzacq, France, and Middle to Late Eocene of Germany.

**Genus** Pemma Klumpp, 1953

**Type species :** P. rotundum Klumpp, 1953.

**Species :** Pemma angulatum Martini, 1959b.

(Pl.4 Fig.8)

**Synonymy :** 1959 Pemma angulatum Martini, p.416, pl.1, figs.1-4.

**Occurrence :** Middle to Late Eocene of the North Sea Basin (NS11,13).

**Range :** Martini (1959) - Eocene of Germany.

Species : Pemma basquensis (Martini) Báldi-Beke, 1971.

(Pl.B. Figs.1,5,9; Pl.15 Figs.15,16)

Synonymy : 1959 Micrantholithus basquensis Martini, p.417, pl.1, figs.9-12.

1971 Pemma basquensis (Martini) Báldi-Beke, p.16.

Occurrence : Middle Eocene of the southern North Sea Basin (NS12-14), and Middle Eocene (NP14-17) of the Isle of Wight.

Range : Bybell and Gartner (1972) - upper Middle Eocene of Alabama and Louisiana, Oregon, France and California, and in the Middle to Late Eocene of Germany and Hungary.

Species : Pemma papillatum Martini, 1959b.

(Pl.13 Figs.11,12)

Synonymy : 1959 Pemma papillatum Martini, p.139; text-fig.1.

See also Bybell and Gartner (1972).

Occurrence : Late Eocene (NP20) of Alabama.

Range : Bybell and Gartner (1972) - upper Middle Eocene of Alabama, the Middle and Late Eocene of Hungary, Mississippi and France, and the Late Eocene of Louisiana.

Species : Pemma rotundum Klumpp, 1953.

Synonymy : 1953 Pemma rotundum Klumpp, p.38, pl.16, figs.3,4; text-figs.2,3.

Occurrence : Late Eocene of 21/11-1 (NS11).

Range : Bybell and Gartner (1972) - Middle Eocene of the Lisbon Formation in Alabama, the Middle Eocene of France and Austria, and in the Middle and Late Eocene of Germany and Hungary.

**Species** : Pemma stradneri (Chang) Perch-Nielsen, 1971c.

(Pl.15 Figs.23)

**Synonymy** : 1969 Micrantholithus stradneri Chang, p.149, pl.1, figs.1-4.

1971 Pemma stradneri (Chang) Perch-Nielsen, p.60, pl.56, figs.2,3.

**Occurrence** : Middle to Late Eocene of the North Sea Basin (NS11-13).

**Range** : Bybell and Gartner (1972) - upper Middle Eocene of Alabama and the Late Eocene of England.

**FAMILY** **Discoasteraceae** Tan Sin Hok, 1927

**Genus** Discoaster Tan Sin Hok, 1927

**Type species** : Discoaster pentaradiatus Tan Sin Hok, 1927.

**Species** : Discoaster adamanteus Bramlette and Wilcoxon, 1967.

**Synonymy** : 1967 Discoaster adamanteus Bramlette and Wilcoxon, p.108-109, pl.7, fig.6.

**Occurrence** : Miocene of the central North Sea Basin (NS3-7).

**Range** : Bramlette and Wilcoxon (1967) - Late Oligocene to Early Miocene of Trinidad; Perch-Nielsen (1985a) - Late Oligocene to early Miocene (NP23-NN3).

**Species** : Discoaster barbadiensis (Tan Sin Hok) Bramlette and Riedel, 1954.

(Pl.14 Fig.11,22)

**Synonymy** : 1934 Heliodiscoaster barbadiensis Tan Sin Hok, p.64, figs.22,23.

1954 Discoaster barbadiensis (Tan Sin Hok) Bramlette and Riedel, p.398-399, pl.39, fig.5a,b

1984 Helio-discoaster barbadiensis (Tan Sin Hok) Theodoridis - Theodoridis, p.146-147, pl.29, figs.4-8.

See Theodoridis (1984) for further references.

**Occurrence** : Eocene of the North Sea Basin (NS11-13,15), Late Eocene (NP20) of Alabama, and Middle Eocene (NP14-16) of the Isle of Wight.

**Range** : Theodoridis (1984) - Eocene (CP9-15b); Perch-Nielsen (1985a) - Eocene (NP10-20).

**Species** : Discoaster bifax Bukry, 1971a.

**Synonymy** : 1971 Discoaster bifax Bukry, p.313-314, pl.3, figs.6-11.

1984 Helio-discoaster bifax (Bukry) Theodoridis - Theodoridis, p.149.

**Occurrence** : Middle Eocene of 49/9-1 (NS13).

**Range** : Bukry (1971a) - Middle Eocene of the Atlantic and Pacific Oceans; Theodoridis (1984) - Middle Eocene (CP14).

**Species** : Discoaster binodosus Martini, 1958.

(Pl.7 Figs.10,11; Pl.14 Fig.19; Pl.16 Fig.18)

**Synonymy** : 1958 Discoaster binodosus Martini, p.361, pl.4, figs.18,19.

1958 Discoaster binodosus binodosus Martini, p.362, pl.4, fig.18.

1958 Discoaster binodosus hirundinus Martini, partim, p.362, pl.4, fig.19a; non pl.4, fig.19b.

1984 Helio-discoaster binodosus (Martini) Theodoridis - Theodoridis, p.150-151.

See Theodoridis (1984) for further references.

**Occurrence** : Early to Middle Eocene of the North Sea Basin (NS13-15), Early Eocene (NP11-12) of the London Clay Formation, North London area, Middle Eocene (NP17) of the Isle of Wight.

**Range** : Theodoridis (1984) - Eocene (CP9-15); Perch-Nielsen (1985a) - Eocene (NP9-16).

**Remarks** : This species has 6-8 arms radiating from a central area containing a prominent knob-like projection. Each of the arms have lateral nodes approximately half-way along their length. The notch between each arm is smoothly rounded. Within the study material the number and length of arms on this species was found to be variable, as was the architecture of the arm tip termination. Such variation led Martini (1958) to erect sub-species of D. binodosus, but this is not followed herein because of the potential for variation due solely to preservational effects. D. binodosus was found to be a useful biostratigraphical marker species within the Early Eocene of the study material.

Species : Discoaster deflandrei Bramlette and Riedel, 1954.

(Pl.1 Fig.12; Pl.10 Fig.13; Pl.11 Figs.11,23)

Synonymy : 1954 Discoaster deflandrei Bramlette and Riedel, p.399, pl.39, fig.6; text-fig.1.

1984 Eu-discoaster deflandrei (Bramlette and Riedel) Theodoridis, p.156-157, pl.32, fig.5.

See Theodoridis (1984) for further references.

Occurrence : Late Oligocene to Middle Miocene of the North Sea Basin (NS4-8), Late Oligocene (NP24) of the Hatton-Rockall Basin (ODP-12-117-2-3, 147-148cm).

Range : Perch-Nielsen (1985a) - Late Oligocene to Early Miocene (NP25-NN5).

Species : Discoaster distinctus Martini, 1958.

(Pl.16 Fig.17)

Synonymy : 1958 Discoaster distinctus Martini, p.363, pl.4, fig.17a,b.

1984 Eu-discoaster distinctus (Martini) Theodoridis - Theodoridis, p.155-156, pl.32, figs.1,2.

See Theodoridis (1984) for further references.

Occurrence : Middle Eocene of the southern North Sea Basin (NS12-13), Early to

Middle Eocene (NP12-13,14-16) of the Isle of Wight, and Middle Eocene (NP15-16) of Hampden Beach, New Zealand.

**Range** : Theodoridis (1984) - Early to Middle Eocene (CP10-12).

**Species** : Discoaster elegans Bramlette and Sullivan, 1961.
(Pl.5 Fig.14; Pl.6 Fig.5)

**Synonymy** : 1961 Discoaster elegans Bramlette and Sullivan, p.159, pl.11, fig.16a,b.

1984 Helio-discoaster elegans (Bramlette and Sullivan) Theodoridis - Theodoridis, p.143-144, pl.28, figs.10-12.

See Theodoridis (1984) for further references.

**Occurrence** : Middle Eocene of the southern North Sea Basin (NS12-13).

**Range** : Bramlette and Sullivan (1961) - Early and Middle Eocene of California; Perch-Nielsen (1985a) - Late Palaeocene to Early Eocene (NP9-10).

**Species** : Discoaster exilis Martini and Bramlette, 1963.

**Synonymy** : 1963 Discoaster exilis Martini and Bramlette, p.852, pl.104, figs.1-3.

1984 Eu-discoaster exilis (Martini and Bramlette) Theodoridis - Theodoridis, p.163, pl.12, fig.2; pl.33, figs.3-5.

See Theodoridis (1984) for further references.

**Occurrence** : Early to Middle Miocene of the central North Sea Basin (NS3-6).

**Range** : Theodoridis (1984) - Miocene (NN4-NN9).

**Remarks** : Asterolith (8 - 16um) with 6 (rarely 5) arms which taper outwards and terminate in a slight bifurcation. The central area has a small stellate knob-like projection. Despite its restricted occurrence in the North Sea Basin material, this species was extrememly useful in delimiting the Middle Miocene NS3 zone (equivalent to the NN6 zone of Martini (1971).

Species : Discoaster kuepperi Stradner, 1959.

(Pl.C.Fig.3,7,11,14,18,22; Pl.16 Figs.9,10,24)

Synonymy : 1959 Discoaster kuepperi Stradner, p.478, figs.17-21.

1961 Discoasteroides kuepperi (Stradner) Bramlette and Sullivan, p.163, pl.13, figs.16-19.

1984 Helio-discoaster kuepperi (Stradner) Theodoridis - Theodoridis, p.147-148, pl.29, figs.9-13.

See Theodoridis (1984) for further references.

Occurrence : Early Eocene of the North Sea Basin (NS15), Early Eocene (NP12-13) of the Isle of Wight, and Early Eocene (NP12) of the London Clay Formation, North London area.

Range : Theodoridis (1984) - Early to Middle Eocene (CP10-12).

Remarks : Asterolith composed of 8-10 'petaloid' elements. These elements have a short pointed free portion, and are often ornamented by concentric ridges. The proximal face contains a large stem which flares out to form a funnel-like structure. A small knob-like projection is present on the centre of the distal face. In cross-polarised light the 'stem' exhibits birefringence giving this species very distinctive optical properties. D. kuepperi was found to be a very useful marker species for the Early Eocene of the North Sea Basin and the comparative material, in association with D. lodoensis and also in its absence.

Species : Discoaster lodoensis Bramlette and Riedel, 1954.

(Pl.B. Figs.16,20,24; Pl.16 Figs.21-23)

Synonymy : 1954 Discoaster lodoensis Bramlette and Riedel, p.398, pl.39, fig.3a,b.

1984 Helio-discoaster lodoensis (Bramlette and Riedel) Theodoridis - Theodoridis, p.148, pl.30, figs.4-6.

See Theodoridis (1984) for further references.

**Occurrence :** Early Eocene of the southern North Sea Basin (NS15).

**Range :** Bramlette and Riedel (1954) - Early Eocene of California; Perch-Nielsen (1985a) - Early to Middle Eocene (NP12-14).

**Remarks :** Stellate asterolith consisting of 6 (rarely 5 or 7) arms which are free for approximately 50-60% of their length. The distal portion of each ray tapers gradually to a sharp, slightly curving point. A stem or knob-like projection extends from one surface. The arms display prominent ridges extending radially to one side of the median line. Diameter = 14 - 24um. This species is very distinctive and, despite its rather rare (in terms of abundance) occurrences, it could be used successfully as a marker species in the Early Eocene of the North Sea Basin.

**Species :** Discoaster saipanensis Bramlette and Riedel, 1954.

(Pl.5 Fig.15; Pl.14 Fig.18)

**Synonymy :** 1954 Discoaster saipanensis Bramlette and Riedel, p.398, pl.39, fig.4.

1984 Helio-discoaster saipanensis (Bramlette and Riedel) Theodoridis - Theodoridis, p.149, pl.30, figs.1-3.

See Theodoridis (1984) for further references.

**Occurrence :** Middle to Late Eocene of the North Sea Basin (NS11-12), Late Eocene (NP20) of William's Bluff, New Zealand, Late Eocene (NP19) of the Isle of Wight, Middle Eocene (NP15-16) of Hampden Beach, New Zealand, Late Eocene (NP20) of Alabama.

**Range :** Bramlette and Riedel (1954) - Late Eocene from many localities; Perch-Nielsen (1985a) - Middle to Late Eocene (NP16-20).

**Remarks :** Asterolith with 5 - 8 straight arms which are joined for approximately 50% of their length and which taper to a sharp point. Centrally a stem projects from one of the surfaces. Each arm has a prominently raised ridge extending radially to one side of the median line. Diameter = 9 - 13um. This species differs from D. barbadiensis in the more separated nature of the arms, the fewer number of arms and the more sharply pointed terminations to the arms. D. saipanensis was seen to be a useful marker for the Late Eocene in the comparative material, but its sporadic occurrence in the North Sea Basin material meant that it could not reliably be used biostratigraphically.

Species : Discoaster saundersii Roth and Hay in Hay et al., 1967.

Synonymy : 1967 Discoaster saundersi Roth and Hay in Hay et al., p.453, pl.3, figs.2-6.

Occurrence : Late Oligocene to Early Miocene of the North Sea Basin (NS6-8).

Range : Roth and Hay in Hay et al. (1967) - Late Oligocene of Trinidad.

Species : Discoaster sublodoensis Bramlette and Sullivan, 1961.

(Pl.7 Fig.9)

Synonymy : 1961 Discoaster sublodoensis Bramlette and Sullivan, p.162, pl.12, fig.6a,b.

1984 Helio-discoaster sublodoensis (Bramlette and Sullivan) Theodoridis - Theodoridis, p.149.

See Theodoridis (1984) for further references.

Occurrence : Middle Eocene (NP15-16) of Hampden Beach, New Zealand.

Range : Bramlette and Sullivan (1961) - Middle Eocene of California, Texas, and France; Perch-Nielsen (1985a) - Middle Eocene (NP14-15).

Species : Discoaster tanii Bramlette and Riedel, 1954.

(Pl.B. Figs.3,7,11 & Pl.D. Figs.21,22; Pl.3 Fig.6; Pl.6 Fig.6)

Synonymy : 1954 Discoaster tanii Bramlette and Riedel, p.397, pl.39, fig.19a,b.

1954 Discoaster tanii nodifer Bramlette and Riedel, p.397, pl.39, fig.2.

1967 Discoaster tanii ornatus Bramlette and Wilcoxon, p.112, pl.7, figs.7,8.

1984 Helio-discoaster tanii (Bramlette and Riedel) Theodoridis - Theodoridis, p.153, pl.31, figs.8-10.

See Theodoridis (1984) for further references.

**Occurrence** : Middle Eocene to Late Oligocene of the North Sea Basin (NS8-13), and Middle Eocene (NP15-16) of Hampden Beach, New Zealand.

**Range** : Bramlette and Riedel (1954) - Middle to Late Eocene of Trinidad; Perch-Nielsen (1985a) - Middle Eocene to early Oligocene (NP15-23).

**Species** : Discoaster variabilis Martini and Bramlette, 1963.

(Pl.D. Figs.5,6; Pl.1 Fig.11)

**Synonymy** : 1963 Discoaster variabilis Martini and Bramlette, p.854, pl.104, figs.4-9.

1984 Eu-discoaster variabilis (Martini and Bramlette) Theodoridis - Theodoridis, p.158-159, pl.32, fig.8.

See Theodoridis (1984) for further references.

**Occurrence** : Miocene of the North Sea Basin (NS2-7).

**Range** : Theodoridis (1984) - Early Miocene to Pliocene (NN4-18).

**Species** : Discoaster wemmelensis Achutan and Stradner, 1967.

**Synonymy** : 1967 Discoaster wemmelensis Achutan and Stradner, p.5, pl.4, figs.3,4.

1984 Helio-discoaster wemmelensis (Achutan and Stradner) Theodoridis - Theodoridis, p.145.

**Occurrence** : Middle to Late Eocene of the North Sea Basin (NS11-13), and Middle Eocene (NP17) of the Isle of Wight.

**Range** : Theodoridis (1984) - Early to middle Miocene (CP11-14).

**FAMILY** **Fasciculithaceae** Hay and Mohler, 1967

**Genus** Fasciculithus Bramlette and Sullivan, 1961

**Type species** : F. involutus Bramlette and Sullivan, 1961.

**Species** : Fasciculithus tympaniformis Hay and Mohler in Hay et al., 1967.

(Pl.17 Fig.8)

**Synonymy** : 1967 Fasciculithus tympaniformis Hay and Mohler in Hay et al., p.447, pl.8, figs.1-5; pl.9, figs.1-5.

1979 Fasciculithus tympaniformis Hay and Mohler in Hay et al. - Romein, p.151.

See Romein (1979) for further references.

**Occurrence** : Late Palaeocene of 30/6-2 (NS16), and Late Palaeocene (NP8) of Pegwell Bay, Kent.

**Range** : Romein (1979) - Late Palaeocene to Early Eocene (F. tympaniformis Zone to T. contortus Zone) of Spain and Israel; Perch-Nielsen (1985a) - Late Palaeocene (NP5-9).

**Remarks** : Short, sub-cylindrical form composed of approximately 16 wedge-shaped elements with a smooth outer surface. This species, and other species of Fasciculithus had a restricted occurrence in the North Sea Basin, thus it could be used to accurately date the early Late Palaeocene interval.

**Species** : Fasciculithus ulii Perch-Nielsen, 1971b.

**Synonymy** : 1971 Fasciculithus ulii Perch-Nielsen, p.350, pl.2, figs.1-4; pl.14, figs.17,18.

1979 Fasciculithus ulii Perch-Nielsen - Romein, p.149, pl.4, fig.7.

**Occurrence :** Late Palaeocene of 30/6-2 (NS16).

**Range :** Romein (1979) - Early/Late Palaeocene (E. macellus Zone, F. tympaniformis Zone) of Spain and Israel; Perch-Nielsen (1985a) - Early/Late Palaeocene (NP4-5).

**Remarks :** A large species of Fasciculithus, with an irregular outer surface. This species occurred in association with F. tympaniformis in the early part of the late Palaeocene in the North Sea Basin study material.

**FAMILY** **Goniolithaceae** Deflandre, 1957

**Genus** Goniolithus Deflandre, 1957

**Type species :** Goniolithus fluckigeri Deflandre, 1957.

**Species :** Goniolithus fluckigeri Deflandre, 1957.

(Pl.5 Fig.6; Pl.14 Fig.24)

**Synonymy :** 1957 Goniolithus fluckigeri Deflandre, p.2539-2541, figs.1-4.

1968 Goniolithus fluckigeri Deflandre - Stradner in Stradner and Edwards, p.42-43, pl.41, figs.1,2; text-figs.8.1,2a-f.

See Stradner and Edwards (1968) for further references.

**Occurrence :** Late Oligocene of 29/10-1 (NS8), and Middle Eocene (NP14-16) of the Isle of Wight.

**Range :** Stradner and Edwards (1968) - Palaeocene to Late Eocene of Europe.

**FAMILY** **Heliolithaceae** Hay and Mohler, 1967

**Genus** Heliolithus Bramlette and Sullivan, 1961

**Type species :** H. riedelii Bramlette and Sullivan, 1961.

**Species :** Heliolithus riedelii Bramlette and Sullivan, 1961.

(Pl.A. Figs.1,5,9; Pl.7 Figs.12,13)

**Synonymy :** 1961 Heliolithus riedelii Bramlette and Sullivan, p.164, pl.14, figs.9a-c,10-11.

**Occurrence :** Late Palaeocene (NP8) of Pegwell Bay, Kent.

**Range :** Perch-Nielsen (1985a) - Late Palaeocene (NP8).

**FAMILY** **Lithostromationaceae** Haq, 1967

**Genus** Lithostromation Deflandre, 1942

**Type species :** L. perdurum Deflandre, 1942.

**Species :** Lithostromation perdurum Deflandre, 1942.

(Pl.5 Fig.9; Pl.10 Fig.5)

**Synonymy :** 1942 Lithostromation perdurum Deflandre, p.918, figs.1-9.

1971 Lithostromation perdurum Deflandre - Perch-Nielsen, p.61, pl.57, fig.6.

1975 Lithostromation perdurum Deflandre - Bybell, p.202-204, pl.19, fig.6.

See Bybell (1975) for further references.

**Occurrence :** Middle Eocene to Middle Oligocene and Miocene of the North Sea Basin (NS2-3,7,9-13), and Middle Eocene (NP14-16) of the Isle of Wight.

**Range :** Bybell (1975) - upper Middle Eocene of Alabama and from the Eocene to the Pliocene in other localities.

**Species :** Lithostromation simplex (Klumpp) Bybell, 1975.

**Synonymy :** 1953 Trochaster simplex Klumpp, pl.16, fig.7; text-fig.4.2.

1975 Lithostromation simplex (Klumpp) Bybell, p.204-206, pl.19, fig.2.

See Bybell (1975) for further references.

**Occurrence :** Middle Miocene of 29/10-1 (NS3).

**Range :** Bybell (1975) - Middle Eocene of Alabama and throughout the Eocene and Oligocene of other sections.

**FAMILY** **Sphenolithaceae** Deflandre in Grassé, 1952

**Genus** Sphenolithus Deflandre in Grassé, 1952

**Type species** : Sphenolithus radians Deflandre in Grassé, 1952.

**Species** : Sphenolithus abies Deflandre in Deflandre and Fert, 1954.

**Synonymy** : 1954 Sphenolithus abies Deflandre in Deflandre and Fert, p.164, pl.10, figs.1-4.

1970 Sphenolithus abies Deflandre - Roth et al., p.1105, pl.5, figs.7-8.

1984 Sphenolithus abies Deflandre - Theodoridis, p.87, pl.8, figs.8,9.

See Roth et al. (1970) for further references.

**Occurrence** : Late Miocene of the North Sea Basin (NS2).

**Range** : Roth et al. (1970) - Pliocene; Perch-Nielsen (1985a) - Late Miocene to Pliocene (NN9-15).

**Species** : Sphenolithus anarrhopus Bukry and Bramlette, 1969.

(Pl.17 Fig.5)

**Synonymy** : 1969 Sphenolithus anarrhopus Bukry and Bramlette, p.140, pl.3, figs.5-8.

1979 Sphenolithus anarrhopus Bukry and Bramlette - Romein, p.145.

1983 Sphenolithus anarrhopus Bukry and Bramlette - Aubry, p.146, pl.1, figs.9-13.

See Romein (1979) for further references.

**Occurrence** : Late Palaeocene (NP8) of Pegwell Bay, Kent, and early Eocene (NP11) of the London Clay Formation, North London area.

**Range** : Romein (1979) - Late Palaeocene (H. kleinpellii, D. mohleri Zone) of Spain; Perch-Nielsen (1985a) - Late Palaeocene to Early Eocene (NP6-11).

**Species** : *Sphenolithus belemnos* Bramlette and Wilcoxon, 1967.

(Pl.11 Figs.1-8)

**Synonymy** : 1967 *Sphenolithus belemnos* Bramlette and Wilcoxon, p.118, pl.2, figs.1-3.

1970 *Sphenolithus belemnos* Bramlette and Wilcoxon - Roth *et al.*, p.1104, pl.4, figs.1-8.

**Occurrence** : Early Miocene of the North Sea Basin (NS6).

**Range** : Perch-Nielsen (1985a) - Early Miocene (NN2-3).

**Remarks** : A narrow, dart-shaped sphenolith in side view. It shows a uniform taper up to the pointed apical spine. In cross- polarised light this species exhibits a distinctive outline, differing from *S. heteromorphus*, in having a taller basal section, and more rounded apical spine. *S. belemnos* was used widely in the North Sea Basin to indicate the NS6 zone (equivalent to the NN3 zone of Martini, 1971).

**Species** : *Sphenolithus capricornutus* Bukry and Percival, 1971.

**Synonymy** : 1971 *Sphenolithus capricornutus* Bukry and Percival, p.140, pl.6, figs.4-6.

**Occurrence** : Early Eocene and Late Oligocene of the central North Sea Basin (NS8,15).

**Range** : Bukry and Percival (1971) - Late Oligocene to Early Miocene of the south Atlantic Ocean; Perch-Nielsen (1985a) - Late Oligocene to Early Miocene (NP25-NN1).

**Species** : *Sphenolithus celsus* Haq, 1971.

**Synonymy** : 1971 *Sphenolithus celsus* Haq, p.121, pl.1, figs.1-5; pl.5, fig.4.

1983 *Sphenolithus celsus* Haq - Aubry, p.147, pl.7, figs.17-24.

**Occurrence** : Late Eocene of 49/9-1 (NS11).

**Range** : Aubry (1983) - Middle to Upper Barton Beds (Middle Eocene) of the Anglo-Paris Basin; Perch-Nielsen (1985a) Late Eocene to Early Oligocene.

**Species** : Sphenolithus ciperoensis Bramlette and Wilcoxon, 1967.

**Synonymy** : 1967 Sphenolithus ciperoensis Bramlette and Wilcoxon, p.120, pl.2, figs.15-20.

**Occurrence** : Late Oligocene of the North Sea Basin (NS8).

**Range** : Bramlette and Wilcoxon (1967) - Late Oligocene of Trinidad; Perch-Nielsen (1985a) - Late Oligocene (NP24-25).

**Species** : Sphenolithus compactus Backman, 1980.

**Synonymy** : 1980 Sphenolithus compactus Backman, p.59-60, pl.3, fig.20,21.

**Occurrence** : Middle/Late Miocene of 29/10-1 (NS2).

**Range** : Backman (1980) - Early Miocene to middle Late Miocene of the Hatton-Rockall Basin; Perch-Nielsen (1985a) - Miocene (NN1-10).

**Species** : Sphenolithus conicus Bukry, 1971a.

**Synonymy** : 1971 Sphenolithus conicus Bukry, p.320, pl.5, figs.10-12.

**Occurrence** : Early Miocene of 21/11-1 (NS6).

**Range** : Bukry (1971a) - Early Miocene of the Pacific Ocean; Perch-Nielsen (1985a) - Early Miocene (NN1-3).

**Remarks** : A 'squat' form, it has been compared to S. heteromorphus (Perch-Nielsen, 1985, p.522), but in the sample material it could be more closely compared with S. belemnos which also has a similar stratigraphic distribution. In side view S. conicus has a lower apical spine than S. belemnos and a slightly broader basal section.

**Species** : Sphenolithus distentus (Martini) Bramlette and Wilcoxon, 1967.

**Synonymy** : 1965 Furcatolithus distentus Martini, p.407, pl.35, figs.7-9.

1967 Sphenolithus distentus (Martini) Bramlette and Wilcoxon, p.122, pl.1, fig.5; pl.2, figs.4,5.

See Roth et al. for further references.

**Occurrence** : Early Oligocene (NP21) of Alabama.

**Range** : Bramlette and Wilcoxon (1967) - Late Oligocene of Trinidad; Perch-Nielsen (1985a) - Late Oligocene (NP23-25).

**Species** : Sphenolithus furcatolithoides Locker, 1967a.

(Pl.14 Figs.1,2,5,6)

**Synonymy** : 1967 Sphenolithus furcatolithoides Locker, p.363, pl.1, figs.14-16; text-figs.7,8.

See Romein (1979) for further references.

**Occurrence** : Eocene of the North Sea Basin (NS11-14).

**Range** : Romein (1979) - Middle Eocene (N. fulgens Zone) of Spain; Perch-Nielsen (1985a) - Middle Eocene (NP15-16).

**Remarks** : A very distinctive species of Sphenolithus which has two long apical spines (usually broken) and a short proximal column. The spines are bright under cross-polarised light at 0°, but disappear at 45°. In the study material they often had a sturdy appearance due to overgrowth. S. furcatolithoides was found to be useful in the North Sea Basin study material for delimiting the upper part of the NP14 zone (Martini, 1971) below the LDO of Nannotetrina species, and in the absence of Discoaster sublodoensis .

**Species** : Sphenolithus heteromorphus Deflandre, 1953.

(Pl.10 Figs.14,21-24)

**Synonymy** : 1953 Sphenolithus heteromorphus Deflandre, p.1785-1786, figs.1,2.

See Roth et al. for further references.

**Occurrence** : Early to Middle Miocene of the North Sea Basin (NS4-5).

**Range** : Perch-Nielsen (1985a) - Early to Middle Miocene (NN4-5).

**Remarks** : This is another very distinctive species of the Sphenolithus genus. It has a low proximal column and a high apical spine. The spine is visible in cross-polarised light at 45°, and disappears at 0°. The spine of this species is much higher and more sharply pointed than the spine of S. belemnos. S. heteromorphus was a consistent and useful member of the Middle Miocene assemblages recovered from the North Sea Basin study material and could be used to identify the equivalent of the NN5 zone of Martini (1971).

**Species** : Sphenolithus moriformis (Brönnimann and Stradner) Bramlette and Wilcoxon, 1967.

(Pl.A. Figs.14,18,22; Pl.C. Figs.16,20,24; Pl.1 Figs.10,13; Pl.3 Fig.13)

**Synonymy** : 1960 Nannoturbella moriformis Brönnimann and Stradner, p.368, figs.11-16.

1967 Sphenolithus moriformis (Brönnimann and Stradner) Bramlette and Wilcoxon, p.124-126, pl.3, figs.1-6.

1984 Sphenolithus moriformis (Brönnimann and Stradner) Bramlette and Wilcoxon - Theodoridis, p.87, pl.8, figs.1-3.

See Roth et al. for further references.

**Occurrence** : Early Oligocene to Late Miocene of the North Sea Basin (NS2-14), and throughout the Tertiary in many of the other sections studied.

**Range** : Bramlette and Wilcoxon (1967) - Palaeocene to Miocene of many regions; Perch-Nielsen (1985a) - Early Eocene to Late Miocene (NP12-NN9).

Species : Sphenolithus neoabies Bukry and Bramlette, 1969.

Synonymy : 1969 Sphenolithus neoabies Bukry and Bramlette, p.140, pl.3, figs.9-11.

Occurrence : Late Miocene of 29/10-1 (NS2).

Range : Perch-Nielsen (1985a) - Late Miocene to Pliocene (NN12-16).

Species : Sphenolithus predistentus Bramlette and Wilcoxon, 1967.

(Pl.13 Fig.2)

Synonymy : 1967 Sphenolithus predistentus Bramlette and Wilcoxon, p.126, pl.1, fig.6; pl.2, figs.10-11.

Occurrence : Late Eocene of 49/9-1 (NS11), Early Oligocene (NP21) of JOIDES Hole 5, Late Eocene to Early Oligocene (NP20-21) of Alabama, and Middle Eocene (NP17) of Hampden Beach, New Zealand.

Range : Bramlette and Wilcoxon (1967) - Late Oligocene of Trinidad; Perch-Nielsen (1985a) - Late Eocene to Late Oligocene (NP17-24).

Species : Sphenolithus primus Perch-Nielsen, 1971b.

Synonymy : 1971 Sphenolithus primus Perch-Nielsen, p.357, pl.11, fig.4; pl.12, figs.4,5,7-12; pl.14, figs.22-24.

See Romein (1979) for further references.

Occurrence : Early Eocene of 49/10-1 (NS15), and Early Eocene (NP11) of the London Clay Formation, North London area.

Range : Romein (1979) - Early Palaeocene to Early Eocene (E. macellus Zone to D. binodosus Zone) of Spain and Israel; Perch-Nielsen (1985a) - Early Palaeocene to Early Eocene (NP4-11).

**Species** : *Sphenolithus pseudoradians* Bramlette and Wilcoxon, 1967.

**Synonymy** : 1967 *Sphenolithus pseudoradians* Bramlette and Wilcoxon, p.126-128, pl.2, figs.12-14.

1970 *Sphenolithus pseudoradians* Bramlette and Wilcoxon - Roth *et al.*, p.1103, pl.1, fig.3.

**Occurrence** : Early Eocene and Late Oligocene of the North Sea Basin (NS8,15), Early Oligocene (NP21) of Alabama, and Early Oligocene (NP21) of JOIDES Hole 5.

**Range** : Bramlette and Wilcoxon (1967) - Late Eocene to Early Oligocene of Trinidad; Perch-Nielsen (1985a) - Middle Eocene to Late Oligocene (NP15-24).

**Species** : *Sphenolithus radians* Deflandre *in* Grassé, 1952.

(Pl.17 Fig.6)

**Synonymy** : 1952 *Sphenolithus radians* Deflandre *in* Grassé, p.466, fig.343J-K; fig.363A-G.

1975 *Sphenolithus radians* Deflandre *in* Grassé - Bybell, p.234-236, pl.23, fig.1.

See Bybell (1975) for further references.

**Occurrence** : Early to Middle Eocene of the North Sea Basin (NS13-15), Early Eocene of the Isle of Wight (NP12-13), and Early Eocene (NP11-12) of the London Clay Formation, North London area.

**Range** : Romein (1979) - Early to Middle Eocene (T. contortus Zone to N. fulgens Zone) of Spain and Israel; Perch-Nielsen (1985a) - Early to Late Eocene (NP11-19).

**ORDER** **EIFFELLITHALES** Rood, Hay and Barnard, 1971

**FAMILY** **Pontosphaeraceae** Lemmermann, 1908

Genus Pontosphaera Lohmann, 1902

Type species : P. syracusana, Lohmann, 1902.

Species : Pontosphaera discopora Schiller, 1925.

Synonymy : 1925 Pontosphaera discopora Schiller, p.11, pl.1, fig.4.

Occurrence : Late Miocene of 21/30-1 (NS2).

Range : Schiller (1925) - Miocene to Pliocene.

Species : Pontosphaera exilis (Bramlette and Sullivan) Romein, 1979.

(Pl.C. Figs.1,5,9; Pl.16 Figs.13,14; Pl.17 Fig.4)

Synonymy : 1961 Discolithus exilis Bramlette and Sullivan, p.142, pl.2, fig.10a-c.

1971 Transversopontis exilis (Bramlette and Sullivan) Perch-Nielsen, p.38, pl.27, figs.3,5,6; pl.31, fig.4.

1979 Pontosphaera exilis (Bramlette and Sullivan) Romein p.179.

Occurrence : Early Eocene of the North Sea Basin (NS15).

Range : Bramlette and Sullivan (1961) - Middle Eocene of California and Louisiana; Steurbaut (1988) - Early Eocene (NP12) of Belgium.

Species : Pontosphaera japonica (Takayama) Nishida, 1971.

Synonymy : 1967 Discolithina japonica Takayama, p.177,181,189, pl.2, fig.11; pl.9; pl.10; text-figs.6,7.

1971 Pontosphaera japonica (Takayama) Nishida, p.152, pl.16, figs.10,11.

Occurrence : Early Miocene of 21/11-1 (NS6-7).

Range : Nishida (1971) - Miocene of Japan.

Species : Pontosphaera multipora (Kamptner) Roth, 1970.

(Pl.A. Figs.4,8,12; Pl.B. Figs.4,8,12; Pl.1 Fig.7; Pl.5 Fig.3; Pl.11 Figs.13,14)

**Synonymy :** 1948 _Discolithus multiporus_ Kamptner, p.5, pl.1, fig.9.

1968 _Discolithina multipora_ (Kamptner) Stradner and Edwards, p.35-37, pl.32-35; text-fig.7a-b.

1970 _Pontosphaera multipora_ (Kamptner) Roth, p.860-861.

See Stradner and Edwards (1968) for further references.

**Occurrence :** Early Eocene to Late Miocene of the North Sea Basin (NS2-14), and throughout the Tertiary of many of the other sections studied.

**Range :** Stradner and Edwards (1968) - Middle Eocene to Miocene of Europe, North and Central America.

**Species :** _Pontosphaera ocellata_ (Bramlette and Sullivan) Perch-Nielsen 1984.

**Synonymy :** 1961 _Discolithus ocellatus_ Bramlette and Sullivan, p.142, pl.3, fig.2a-c.

1984 _Pontosphaera ocellata_ (Bramlette and Sullivan) Perch-Nielsen, p.44.

**Occurrence :** Early Eocene (NP11-12) of the London Clay Formation, North London area.

**Range :** Bramlette and Sullivan (1961) - Early to Middle Eocene of California.

**Species :** _Pontosphaera plana_ (Bramlette and Sullivan) Haq, 1971.

(Pl.15 Figs.11,12)

**Synonymy :** 1961 _Discolithus planus_ Bramlette and Sullivan, p.143, pl.3, fig.7a-c.

1971 _Pontosphaera plana_ (Bramlette and Sullivan) Haq, p.22, pl.10, fig.1; pl.12, fig.6.

**Occurrence :** Middle Eocene to Late Oligocene of the North Sea Basin (NS8-13), and Early Oligocene (NP21) of Alabama.

**Range** : Bramlette and Sullivan (1961) - Early to Middle Eocene of California and Texas, and Middle Eocene (Lutetian) of Donzacq, France.

**Species** : Pontosphaera wechesensis (Bukry and Percival) Aubry, 1983

**Synonymy** : 1971 Syracosphaera ? wechesensis Bukry and Percival, p.142, pl.7, figs.7-10.

1975 Discolithina wechesensis (Bukry and Percival) Bybell, p.210, pl.22, fig.2.

1983 Pontosphaera wechesensis (Bukry and Percival) Aubry, p.159, pl.6, fig.33.

See Bybell (1975) for further references.

**Occurrence** : Middle Eocene of 49/10-1 (NS12), and Late Eocene to Early Oligocene (NP20-21) of Alabama.

**Range** : Bukry and Percival (1971) - Lower Middle Eocene of Texas and the Caucasus region of U.S.S.R; Bybell (1975) - Middle Eocene of Alabama, and the Eocene of Denmark.

**Genus** Transversopontis Hay, Mohler and Wade, 1966.

**Type species** : Discolithus obliquipons Deflandre, 1954.

**Species** : Transversopontis obliquipons (Deflandre) Hay, Mohler and Wade.

**Synonymy** : 1954 Discolithus obliquipons Deflandre, p.139, pl.11, figs.1,2.

1966 Transversopontis obliquipons (Deflandre) Hay, Mohler and Wade, p.391-392, pl.8, fig.5.

See Bybell (1975) for further references.

**Occurrence** : Middle Eocene to Early Oligocene of the North Sea Basin (NS10-13), Late Eocene to Early Oligocene (NP20-21) of Alabama, Middle to Late Eocene (NP15-19) of Hampden Beach, New Zealand, and Late Eocene (NP20) of

William's Bluff, New Zealand.

Range : Bybell (1975) - Eocene to Oligocene worldwide.

Species : Transversopontis pulcheroides (Sullivan) Báldi-Beke, 1971.

Synonymy : 1964 Discolithus pulcheroides Sullivan, p.183, pl.4, fig.7a,b

1971 Transversopontis pulcheroides (Sullivan) Báldi-Beke, p.17.

See Stradner and Edwards (1968) for further references.

Occurrence : Middle Eocene to Early Oligocene of the North Sea Basin (NS10-13), Late Eocene (NP20) of William's Bluff, New Zealand, and Middle to Late Eocene (NP15-19) of Hampden Beach, New Zealand.

Range : Stradner and Edwards (1968) - Palaeocene to Late Eocene of Europe and North America.

Species : Transversopontis pulchra (Deflandre in Deflandre and Fert) Perch-Nielsen, 1967b

(Pl.5 Figs.8,10; Pl.7 Fig.1; Pl.13 Figs.7,8)

Synonymy : 1954 Discolithus pulcher Deflandre in Deflandre and Fert, p.142, pl.12, figs,17,18.

1967 Transversopontis pulcher (Deflandre in Deflandre and Fert) Perch-Nielsen, partim p.27, pl.3, figs.9-11; non pl.1, fig.1.

Occurrence : Eocene to Early Oligocene of the North Sea Basin (NS10-15), Late Eocene to Early Oligocene (NP20-21) of Alabama, Middle to Late Eocene (NP15-19) of Hampden Beach, New Zealand, Early to Middle Eocene (NP11-17) of the Isle of Wight, and Late Eocene (NP20) of William's Bluff, New Zealand.

Range : Perch-Nielsen (1971c) - Eocene of Denmark.

Species : Transversopontis rectipons (Haq) Roth, 1970.

(Pl.17 Figs.1,2)

Synonymy : 1968 Discolithina rectipons Haq, p.39-40, pl.7, figs.7-9; pl.11, fig.1.

1970 Transversopontis rectipons (Haq) Roth, p.861.

Occurrence : Early Eocene (NP11-12) of the London Clay Formation, North London area

Range : Roth (1970) - Early Oligocene (E. subdisticha Zone) of Alabama.

Species : Transversopontis zigzag Roth and Hay in Hay et al., 1967.

Synonymy : 1967 Transversopontis zigzag Roth and Hay in Hay et al., p.450, pl.7, figs.4-6.

1967 Discolithina pygmaea Locker, p.761, pl.1, fig.2; pl.2, figs.2,3.

Occurrence : Late Oligocene of the central North Sea Basin (NS8).

Range : Roth and Hay in Hay et al.(1967) - Oligocene (C. margaritae Zone to R. laevis Zone) of JOIDES Hole 5, Blake Plateau.

FAMILY Zygodiscaceae Hay and Mohler ex Bown, 1987

Genus Isthmolithus Deflandre in Deflandre and Fert, 1954

Type species : I. recurvus Deflandre in Deflandre and Fert, 1954.

Species : Isthmolithus recurvus Deflandre in Deflandre and Fert, 1954.

(Pl.5 Figs.4,5; Pl.7 Fig.3; Pl.13 Fig.1,5,6)

Synonymy : 1954 Isthmolithus recurvus Deflandre in Deflandre and Fert, p.169, pl.12, figs.9-13.

Occurrence : Late Eocene to Early Oligocene of the North Sea Basin (NS10-11), Late Eocene to Early Oligocene (NP20-21) of Alabama, Late Eocene (NP19) of Hampden Beach, New Zealand, and Late Eocene (NP20) of William's Bluff, New

Zealand.

Range : Perch-Nielsen (1985a) - Late Eocene to Early Oligocene (NP19-22).

Genus <u>Neochiastozygus</u> Perch-Nielsen, 1971d

Type species : <u>N. perfectus</u> Perch-Nielsen, 1971d.

Species : <u>Neochiastozygus chiastus</u> (Bramlette and Sullivan) Perch-Nielsen, 1971d.

Synonymy : 1961 <u>Zygolithus chiastus</u> Bramlette and Sullivan, p.149, pl.6, figs.1a-d,2a-b,3a-b.

1971 <u>Neochiastozygus chiastus</u> (Bramlette and Sullivan) Perch-Nielsen, p.58-59, pl.4, fig.5; pl.7, figs.13-15.

Occurrence : Late Palaeocene (NP8) of Pegwell Bay, Kent.

Range : Perch-Nielsen (1985a) - Late Palaeocene (NP8-9).

Species : <u>Neochiastozygus eosaepes</u> Perch-Nielsen, 1981b.

Synonymy : 1979 <u>Neochiastozygus saepes</u> early form, Perch-Nielsen, p.136, pl.2, fig.1.

1981 <u>Neochiastozygus eosaepes</u> Perch-Nielsen, p.837-838, pl.5, figs.9-13.

Occurrence : Early Palaeocene of 16/8-1 (NS18).

Range : Van Heck and Prins (1987) - Early Palaeocene (N. saepes Zone to N. perfectus Zone) of the North Sea Basin; Perch-Nielsen (1985a) - Early/Late Palaeocene (NP4-5)

Species : <u>Neochiastozygus modestus</u> Perch-Nielsen, 1971d.

(Pl.17 Fig.20)

Synonymy : 1971 <u>Neochiastozygus modestus</u> Perch-Nielsen, p.62-63, pl.5, figs.5-8; pl.7, figs.22,23.

1987 Neochiastozygus modestus Perch-Nielsen - Van Heck and Prins, p.291, pl.1, figs.15,16; text-fig.13a,b.

**Occurrence** : Palaeocene of the North Sea Basin (NS16-20).

**Range** : Van Heck and Prins (1987) - Early Palaeocene (N. modestus Zone to C. inconspicuus Zone) of the North Sea Basin; Perch-Nielsen (1985a) - Early to Late Palaeocene (NP3-5).

**Species** : Neochiastozygus perfectus Perch-Nielsen, 1971d.

(Pl.8 Fig.6,13; Pl.17 Figs.9-12)

**Synonymy** : 1971 Neochiastozygus perfectus Perch-Nielsen, p.63-64, pl.6, figs.1,2; pl.7, figs.24,25.

1979 Neochiastozygus perfectus Perch-Nielsen - Romein, p.135.

1987 Neochiastozygus perfectus Perch-Nielsen - Van Heck and Prins, p.291, pl.1 fig.19; text-fig.13c.

**Occurrence** : Palaeocene of the North Sea Basin (NS16-18), and Late Palaeocene (NP8) of Pegwell Bay, Kent.

**Range** : Perch-Nielsen (1985a) - Late Palaeocene (NP5-8); Van Heck and Prins (1987) - Early to late Palaeocene (upper C. inconspicuus Zone to NP5) of the North Sea Basin.

**Remarks** : A relatively large species of Neochiastozygus which is elliptical in outline and which has a slender symmetrical cross structure in the central area. The 'cross' is acutely angled along the short axis of the ellipse. The inner wall appears brighter in cross-polarised light than the outer one. N. perfectus was differentiated from N. modestus by its larger size and its narrower, more slender cross structure. N. perfectus was a consistent and readily recognisable (despite the state of preservation) member of the late Early Palaeocene assemblages in the North Sea Basin material, and could be used to sub-divide the equivalent of the upper part of the NP4 (Martini, 1971) zone.

**Species :** Neochiastozygus rosenkrantzii Perch-Nielsen, 1971d.

**Synonymy :** 1985 Neochiastozygus rosenkrantzii Perch-Nielsen - Perch-Nielsen, p.531.

**Occurrence :** Early Eocene of 29/7-1 (NS15).

**Range :** Perch-Nielsen (1985a) - Early Eocene (NP12).

**Species :** Neochiastozygus saepes Perch-Nielsen, 1971d.

**Synonymy :** 1971 Neochiastozygus saepes Perch-Nielsen, p.64-65, pl.6, figs.3-6; pl.7, figs.7-9.

1979 Neochiastozygus saepes Perch-Nielsen - Romein, p.134.

1987 Neochiastozygus saepes Perch-Nielsen - Van Heck and Prins, p.291, pl.1, figs.22-24,27,28; text-figs.14a,b.

**Occurrence :** Early Palaeocene of the North Sea Basin (NS18).

**Range :** Van Heck and Prins (1987) - Early Palaeocene (N. saepes Zone to N. perfectus Zone) of the North Sea Basin; Perch-Nielsen (1985a) - Early/Late Palaeocene (NP4-5).

**Genus** Neococcolithes Sujkowski, 1931

**Type species :** N. lososnensis Sujkowski, 1931.

**Species :** Neococcolithes dubius (Deflandre) Black, 1967.

(Pl.3 Fig.11,14; Pl.4 Figs.1-3; Pl.7 Fig.7)

**Synonymy :** 1954 Zygolithus dubius Deflandre in Deflandre and Fert, p.149, text-figs.43,44.

1964 Chiphragmalithus dubius (Deflandre) Sullivan, p.179, pl.1, fig.2.

1967 Neococcolithes dubius (Deflandre) Black, p.143.

1979 Neococcolithes dubius (Deflandre) Black - Romein, p.138.

See Romein (1979) for further references.

**Occurrence** : Early Eocene to Early Oligocene of the North Sea Basin (NS10-15), and in the same age of sediment in many of the other sections studied.

**Range** : Romein (1979) - Early to Middle Eocene (T. contortus Zone to N. fulgens Zone) of Spain; Perch-Nielsen (1985a) - Early to Late Eocene (NP11-18).

**Species** : Neococcolithes minutus (Perch-Nielsen) Perch-Nielsen, 1971c.

(Pl.7 Figs.6,8; Pl.14 Figs.3,4)

**Synonymy** : 1967 Zygolithus minutus Perch-Nielsen, p.28, pl.5, figs.6,7.

1971 Neococcolithes minutus (Perch-Nielsen) Perch-Nielsen, p.47, pl.42, figs.1-4.

**Occurrence** : Early to Middle Eocene of the North Sea Basin (NS12-15), Middle Eocene (NP14-17) of the Isle of Wight, Middle Eocene (NP15-17) of Hampden Beach, New Zealand, and Early Eocene (NP11-12) of the London Clay Formation, North London area.

**Range** : Perch-Nielsen (1985a) - Early to Late Eocene (NP13-19).

**Species** : Neococcolithes protenus (Bramlette and Sullivan) Black, 1967.

**Synonymy** : 1961 Zygolithus protenus Bramlette and Sullivan, p.150-151, pl.6, fig.15a,b.

1967 Neococcolithes protenus (Bramlette and Sullivan) Black, p.143.

**Occurrence** : Early to Middle Eocene of the North Sea Basin (NS13-15).

**Range** : Perch-Nielsen (1985a) - Late Palaeocene to Early Eocene (NP5-12).

Genus Neocrepidolithus Romein, 1979

Type species : Crepidolithus neocrassus Perch-Nielsen, 1968.

Species : Neocrepidolithus neocrassus (Perch-Nielsen) Romein, 1979.

(Pl.9 Figs.1,2)

Synonymy : 1968 Crepidolithus neocrassus Perch-Nielsen, p.36, pl.2, fig.9; text-fig.11.

1979 Neocrepidolithus neocrassus (Perch-Nielsen) Romein, p.183, pl.1, fig.6.

Occurrence : Early palaeocene of the North Sea Basin (NS17-18).

Range : Perch-Nielsen (1985a) - Cretaceous to Early Palaeocene (up to NP4).

Genus Placozygus Hoffman, 1970

Type species : Glaukolithus fibuliformis Reinhardt, 1964.

Species : Placozygus sigmoides (Bramlette and Sullivan) Romein, 1979.

(Pl.C. Figs.15,19,23; Pl.9 Fig.3; Pl.17 Figs.23,24)

Synonymy : 1961 Zygodiscus sigmoides Bramlette and Sullivan, p.149, pl.4, fig.11a-e.

1979 Placozygus sigmoides (Bramlette and Sullivan) Romein, p.117-118, pl.1, fig.8.

See Romein (1979) for further references.

Occurrence : Palaeocene of the North Sea Basin (NS16-23) and Late Palaeocene (NP8) of Pegwell Bay, Kent.

Range : Bramlette and Sullivan (1961) - Palaeocene of California, Alabama, the type Thanetian in England and in the upper type Danian of Denmark; Romein (1979) - Early Palaeocene to Early Eocene (C. primus Zone to T. contortus Zone) of Spain and Israel.

ORDER **ISOCHRYSIDALES** Pascher, 1910

FAMILY **Thoracosphaeraceae** Schiller, 1930

Genus Thoracosphaera Kamptner, 1927

Type species : Syracosphaera heimii Lohmann, 1902.

Species : Thoracosphaera operculata Bramlette and Martini, 1964.

(Pl.8 Fig.15)

Synonymy : 1964 Thoracosphaera operculata Bramlette and Martini, p.305-306, pl.5, figs.3-7.

Occurrence : Palaeocene of the North Sea Basin (NS16-16).

Range : Perch-Nielsen (1985a) - Cretaceous to Early Eocene.

ORDER **SYRACOSPHAERALES** Hay, 1977

FAMILY **Helicosphaeraceae** Black, 1971

Genus Helicosphaera Kamptner, 1954

Type species : Coccolithus carteri (Wallich) Kamptner, 1941.

Species : Helicosphaera ampliaperta Bramlette and Wilcoxon, 1967.

(Pl.B. Figs.13,17,21; Pl.1 Figs.3,6,9: Pl.10 Figs.11,12,15)

Synonymy : 1967 Helicosphaera ampliaperta Bramlette and Wilcoxon, p.105, pl.6, figs.1-4.

1984 Helicosphaera ampliaperta (Bramlette and Wilcoxon) Theodoridis, p.124-125, pl.13, fig.1; pl.19, figs.1-4; pl.26, fig.1.

See Theodoridis (1984) for further references.

Occurrence : Early Miocene of the North Sea Basin (NS5-7).

Range : Bramlette and Wilcoxon (1967) - Early Miocene of Trinidad; Theodoridis (1984) - Early Miocene (NN2-4); Perch-Nielsen (1985a) - Early Miocene (NN2-4).

Remarks : This species exhibits a near oval outline, normally showing little of the terminal flange of the distal shield. It is differentiated from other species of the genus by having <u>no</u> central area structure in the large central area opening. *H. ampliaperta* was a consistent and distinctive member of the late Early Miocene assemblages of the North Sea Basin assemblages. It was used to accurately date samples as NS5, equivalent to the NN4 zone of Martini (1971).

Species : *Helicosphaera carteri* (Wallich) Kamptner, 1954.

(Pl.1 Figs.2,5)

Synonymy : 1877 *Coccosphaera carteri* Wallich, p.348, pl.17.

1954 *Helicosphaera carteri* (Wallich) Kamptner, p.21,73, figs.17-19.

1967 *Helicopontosphaera kamptneri* Hay and Mohler, p.448, pl.10, fig.5; pl.11, fig.5.

1984 *Helicosphaera palaeocarteri* Theodoridis, p.131, pl.23, figs.1-4; pl.27, fig.6.

1984 *Helicosphaera carteri* var. *carteri* Theodoridis, p.132, pl.23, fig.5.

1984 *Helicosphaera carteri* var. *burkei* Theodoridis, p.133, pl.23, figs.6,7.

1984 *Helicosphaera carteri* var. *wallichii* Theodoridis, p.133, pl.23, figs.8,9; pl.27, fig.7.

1984 *Helicosphaera carteri* (Wallich) Kamptner - Theodoridis, p.131-132, pl.23, figs.5-9; pl.27, fig.7.

See Jafar and Martini (1975) and Theodoridis (1984) for further references.

Occurrence : Miocene of the North Sea Basin (NS1-7).

Range : Theodoridis (1984) - Early Miocene (NN1) to Recent.

Species : Helicosphaera compacta Bramlette and Wilcoxon, 1967.

(Pl.13 Figs.21,22; Pl.14 Figs.12,20; Pl.15 Figs.5,6)

Synonymy : 1967 Helicosphaera compacta Bramlette and Wilcoxon, p.105, pl.6, figs.5-8.

1984 Helicosphaera compacta Bramlette and Wilcoxon - Theodoridis, p.112, pl.16, figs.6-8; pl.24, fig.7.

See Theodoridis (1984) for further references.

Occurrence : Middle to Late Eocene of the North Sea Basin (NS11-13), Middle Eocene (NP17) of Hampden Beach, New Zealand, and Late Eocene to Early Oligocene (NP20-21) of Alabama.

Range : Bramlette and Wilcoxon (1967) - Early Oligocene of Trinidad, Late Eocene to Oligocene of Mississippi; Theodoridis (1984) - Middle Eocene to Late Oligocene (CP14-19).

Species : Helicosphaera dinesenii (Perch-Nielsen) Jafar and Martini, 1975.

(Pl.D. Figs.17,18,19,20)

Synonymy : 1971 Helicopontosphaera dinesenii Perch-Nielsen, p.42,43, pl.35, figs.3,4; pl.36, figs.3,6,9,11; pl.61, figs.6,7.

1975 Helicosphaera dinesenii (Perch-Nielsen) Jafar and Martini, p.390.

1984 Helicosphaera dinesenii (Perch-Nielsen) Jafar and Martini - Theodoridis, p.111, pl.24, fig.4.

See Theodoridis (1984) for further references.

Occurrence : Middle Eocene of the southern North Sea Basin (NS12-13), Middle Eocene (NP15-17) of Hampden Beach, New Zealand.

Range : Theodoridis (1984) - Middle Eocene (CP13-14); Perch-Nielsen (1985a) - Middle Eocene (NP15-16).

**Species** : Helicosphaera euphratis Haq, 1966.

(Pl.7 Fig.2; Pl.11 Figs.19,20,24)

**Synonymy** : 1966 Helicosphaera euphratis Haq, p.33, pl.2, figs.1,3.

1984 Helicosphaera euphratis Haq - Theodoridis, p.121, pl.22, figs.1,2; pl.27, fig.3.

See Theodoridis (1984) for further references.

**Occurrence** : Middle Eocene to Late Oligocene of the North Sea Basin (NS8-13), Early Oligocene (NP21) of Joides Hole 5, Late Eocene to Early Oligocene (NP20-21) of Alabama.

**Range** : Theodoridis (1984) - Late Eocene to Early Miocene (CP15-CN1); Perch-Nielsen (1985a) - Late Eocene to Middle Miocene (NP18-NN5).

**Species** : Helicosphaera intermedia Martini, 1965.

**Synonymy** : 1965 Helicosphaera intermedia Martini, p.404, pl.35, figs.1,2.

1984 Helicosphaera intermedia Martini - Theodoridis, p.121-122, pl.22, fig.3; pl.27, fig.4.

See Theodoridis (1984) for further references.

**Occurrence** : Middle Eocene to Late Miocene of the North Sea Basin (NS2-12), and Late Oligocene (NP24) of the Hatton-Rockall Basin (DSDP-12-117-2-3, 147-148cm).

**Range** : Theodoridis (1984) - Oligocene to Late Miocene (CP16-CN7); Perch-Nielsen (1985a) - Late Eocene to Middle Miocene (NP19-NN5).

**Species** : Helicosphaera lophota Bramlette and Sullivan, 1961.

(Pl.4 Fig.9; Pl.16 Figs.1,2)

**Synonymy** : 1961 Helicosphaera lophota Bramlette and Sullivan, p.144, pl.4, figs.3a,b,4.

1984 Helicosphaera lophota Bramlette and Sullivan - Theodoridis, p.109-110, pl.24, fig.1.

See Theodoridis (1984) for further references.

**Occurrence** : Middle to Late Eocene of 49/9-1 (NS11-13).

**Range** : Bramlette and Sullivan (1961) - Early to Middle Eocene of California, Texas and Donzacq, France; Theodoridis (1984) - Eocene (CP10-15).

**Species** : Helicosphaera obliqua Bramlette and Wilcoxon, 1967.

**Synonymy** : 1967 Helicosphaera obliqua Bramlette and Wilcoxon, p.106, pl.5, figs.13,14.

1984 Helicosphaera obliqua Bramlette and Wilcoxon - Theodoridis, p.116, pl.17, fig.5; pl.25, fig.4.

See Theodoridis (1984) for further references.

**Occurrence** : Late Oligocene to Miocene of the North Sea Basin (NS3-8).

**Range** : Bramlette and Wilcoxon (1967) - Late Oligocene and Early Miocene of Trinidad, early Miocene of Italy; Perch-Nielsen (1985a) - Late Oligocene to Early Miocene (NP24-NN4).

**Species** : Helicosphaera perchnielsenae (Haq) Jafar and Martini, 1975.

**Synonymy** : 1971 Helicopontosphaera perchnielsenasae Haq, p.116, pl.10, figs.5-7.

1973 Helicopontosphaera perchnielseniae Haq - Haq, p.42, pl.4, fig.5; pl.5, figs.5,6.

1975 Helicosphaera perchnielseniae (Haq) Jafar and Martini, p.391.

1984 Helicosphaera perchnielseniae (Haq) Jafar and Martini - Theodoridis, p.115, pl.13, fig.3; pl.17, figs.3,4; pl.25, fig.1.

See Theodoridis (1984) for further references.

**Occurrence** : Miocene of 29/10-1 (NS3,6).

**Range** : Theodoridis (1984) - Early Oligocene to Early Miocene (CP17-CN4).

**Species** : Helicosphaera recta (Haq) Jafar and Martini, 1975.

(Pl.B. Figs.2,6,10; Pl.3 Figs.1,3; Pl.12 Figs.9,10)

**Synonymy** : 1966 Helicosphaera seminulum subsp. recta Haq, p.34, pl.2, fig.6; pl.3, fig.4.

1967 Helicosphaera truncata Bramlette and Wilcoxon, p.106-107, pl.6, figs.13,14.

1969 Helicopontosphaera recta (Haq) Martini, p.136.

1975 Helicosphaera recta (Haq) Jafar and Martini, p.391.

1984 Helicosphaera recta (Haq) Jafar and Martini - Theodoridis, p.114, pl.17, figs.1,2; pl.25, fig.2.

See Theodoridis (1984) for further references.

**Occurrence** : Late Oligocene of the North Sea Basin (NS8), Late Oligocene (NP24) of the Hatton-Rockall Basin (DSDP-12-117-2-3, 147-148cm).

**Range** : Theodoridis (1984) - Late Oligocene to Early Miocene (CP19-CN1a); Perch-Nielsen (1985a) - Late Oligocene (NP25).

**Remarks** : A distinctive species due to its rounded rectangular outline. The central area has two large, rounded pores separated by a horizontal bar. The flange is sharply terminated and pointed. This species was used biostratigraphically in the North Sea Basin to recognise the Late Oligocene.

**Species** : Helicosphaera reticulata Bramlette and Wilcoxon, 1967.

(Pl.13 Figs.17,18; Pl.15 Figs.3,4)

**Synonymy** : 1967 Helicosphaera reticulata Bramlette and Wilcoxon, p.106, pl.6, fig.15.

1970 Helicopontosphaera reticulata (Bramlette and Wilcoxon) Roth, p.863, pl.10, fig.5.

1984 Helicosphaera reticulata Bramlette and Wilcoxon - Theodoridis, p.113, pl.16, figs.3-5; pl.24, fig.8.

See Theodoridis (1984) for further references.

**Occurrence** : Late Eocene to Early Oligocene (NP20-21) of Alabama.

**Range** : Bramlette and Wilcoxon (1967) - Early Oligocene of Alabama and JOIDES borings, Late Eocene of Mississippi and Barbados; Perch-Nielsen (1985a) - Late Eocene to Early Oligocene (NP17-22).

**Species** : Helicosphaera sellii (Bukry and Bramlette) Jafar and Martini, 1975.

(Pl.10 Figs.1,2)

**Synonymy** : 1969 Helicopontosphaera sellii Bukry and Bramlette, p.134, pl.2, figs.3-7.

1975 Helicosphaera sellii (Bukry and Bramlette) Jafar and Martini, p.391.

1984 Helicosphaera sellii (Bukry and Bramlette) Jafar and Martini - Theodoridis, p.128, pl.26, fig.7.

See Theodoridis (1984) for further references.

**Occurrence** : Late Miocene to Pliocene of the North Sea Basin (NS1-2).

**Range** : Bukry and Bramlette (1969) - Late Miocene to Pliocene of Italy, Atlantic Ocean, Gulf of Mexico, and the tropical Pacific Ocean; Perch-Nielsen (1985a) - Late Miocene to Pleistocene (NN10-19).

**Species** : Helicosphaera seminulum Bramlette and Sullivan, 1967.

(Pl.4 Fig.12; Pl.16 Figs.5,6)

**Synonymy** : 1961 Helicosphaera seminulum seminulum Bramlette and Sullivan, p.144, pl.4, figs.1a-c,2.

1984 Helicosphaera seminulum Bramlette and Sullivan - Theodoridis, p.107, pl.15, fig.1; pl.24, fig.2.

See Theodoridis (1984) for further references.

**Occurrence** : Early to Middle Eocene of the southern North Sea Basin, Early Oligocene (NP21) of Joides Hole 5.

**Range** : Bramlette and Sullivan (1961) - Early to Middle Eocene of California and Middle Eocene of Donzacq, France; Perch-Nielsen (1985a) - Early to Middle Eocene (NP12-18).

**Species** : Helicosphaera stalis Theodoridis, 1984.

(Pl.10 Figs.3,4,7,8)

**Synonymy** : 1984 Helicosphaera stalis Theodoridis, p.127, pl.13, fig.6; pl.20, figs.10-12; pl.21, figs.1-12; pl.26, figs.5,6.

**Occurrence** : Middle to Late Miocene of the North Sea Basin (NS2-3).

**Range** : Theodoridis (1984) - Middle to Late Miocene (CP5-9).

**Species** : Helicosphaera mediterranea Müller, 1981.

(Pl.1 Figs.1,4; Pl.11 Figs.12,15,16)

**Synonymy** : 1981 Helicosphaera mediterranea Müller, p.428, pl.1, figs.13,14.

1981 Helicosphaera crouchii Bukry, p.462, pl.5, figs.1-4.

1984 Helicosphaera mediterranea Müller - Theodoridis, p.122-123, pl.22, figs.4-9; pl.27, fig.5.

**Occurrence** : Early Miocene of the North Sea Basin (NS7).

**Range** : Perch-Nielsen (1985a) - Early Miocene (NN1-5); Theodoridis (1984) - Early Miocene (E. deflandrei subzone to H. waltrans subzone).

**Remarks** : A large species of Helicosphaera which has a prominent flange and two very large openings in the central area separated by a bar aligned with the short axis of the helicolith. H. mediterranea was a very distinctive member of the Early Miocene assemblage in the North Sea Basin. It was not seen throughout its published range (restricted to the lower part). It can be readily differentiated from most other helicoliths, although it closely resembles H. truempyi. These species are distinguished by the presence of a 'bar' across the central area in H. mediterranea and a 'bridge' in the case of H. truempyi. H. mediterranea may become widely recognised as a marker for the Early Miocene of the North Sea Basin as a result of this study.

Species : Helicosphaera wilcoxonii (Gartner) Jafar and Martini, 1975.

Synonymy : 1971 Helicopontosphaera wilcoxonii Gartner, p.110, pl.2, figs.1-4.

1975 Helicosphaera wilcoxonii (Gartner) Jafar and Martini, p.391.

Occurrence : Late Oligocene of 21/11-1 (NS8).

Range : Perch-Nielsen (1985a) - Late Eocene to Oligocene (NP18-24).

FAMILY Rhabdosphaeraceae Lemmermann, 1908

Genus Blackites (Hay and Towe) Stradner in Stradner and Edwards, 1968

Type species : Discolithus spinosus Deflandre in Deflandre and Fert, 1954.

Species : Blackites spinosus (Deflandre) Hay and Towe, 1962.

(Pl.3 Fig.15)

Synonymy : 1954 Discolithus spinosus Deflandre in Deflandre and Fert, p.143, pl.14, figs.13-15.

1954 Rhabdolithus rectus Deflandre in Deflandre and Fert, p.157, pl.11, fig.12.

1962 Blackites spinosus (Deflandre) Hay and Towe, p.505, pl.4, fig.5.

1968 Blackites rectus (Deflandre) Stradner in Stradner and Edwards, p.29-30, pl.30; pl.31, figs.1-5; text-fig.4.

See Perch-Nielsen (1971c) for further references.

**Occurrence :** Middle Eocene to Early Oligocene of the North Sea Basin (NS9-14), Early Oligocene (NP21) of Joides Hole 5, Middle to Late Eocene (NP15-19) of Hampden Beach New Zealand, Late Eocene (NP20) of William's Bluff, New Zealand, and Late Eocene to Early Oligocene (NP20-21) of Alabama.

**Range :** Perch-Nielsen (1985a) - Eocene to Middle Oligocene.

**Genus** Naninfula (Perch-Nielsen) Perch-Nielsen, 1971

**Type species :** N. deflandrei Perch-Nielsen, 1968.

**Species :** Naninfula deflandrei Perch-Nielsen, 1968.

(Pl.3 Fig.10; Pl.15 Figs.1,2,24; Pl.16 Figs.3,4,7,8,11,12,15,16,20)

**Synonymy :** 1968 Naninfula deflandrei Perch-Nielsen, p.2299, pl.1, figs.1-9.

1971 Naninfula deflandrei Perch-Nielsen - Perch-Nielsen, p.50-51, pl.45, figs.1,8,9; pl.46, fig.8.

**Occurrence :** Middle to Late Eocene of the southern North Sea Basin (NS11-14).

**Range :** Perch-Nielsen (1971c) - Eocene of Denmark.

**Remarks :** An extremely 'squat' form of rhabdolith, N. deflandrei consists of a base plate surmounted by a dome-like stem. Many different morphotypes were seen in the North Sea Basin material, it is possible that these represented a number of species, or perhaps just variation within a single species (preservational effects ?). More detailed analysis of this genus in SEM would probably resolve this. N. deflandrei was one of the most readily recognisable members of the Eocene assemblages recovered from the study material. It ranged from Middle to Upper Eocene, but had limited biostratigraphical application.

Genus Rhabdosphaera Haeckel, 1894

Type species : R. claviger Murray and Blackman, 1898.

Species : Rhabdosphaera gladius Locker, 1967a.

(Pl.D. Figs.1,2; Pl.14 Figs.13,14; Pl.15 Figs.19,20)

Synonymy : 1967 Rhabdosphaera gladius Locker, p.766, pl.1, fig.8; pl.2, fig.12.

Occurrence : Middle Eocene of the southern North Sea Basin (NS13), and Middle Eocene (NP17 ?) of Hampden Beach, New Zealand.

Range : Perch-Nielsen (1985a) - Middle Eocene (NP15).

Remarks : This rhabdolith, as with N. deflandrei, was readily recognisable in the study material by the transparent nature of its stem in cross-polarised light. R. gladius has a relatively short stem which is slightly inflated in the upper part and which tapers to a blunt point. This species had a very restricted occurrence in the study material and could be used to accurately date the Middle Eocene assemblages equivalent in age to the NP15 zone of Martini (1971).

Range : Perch-Nielsen (1985a) - Middle Eocene.

Species : Rhabdosphaera pseudomorionum Locker, 1967a.

(Pl.13 Figs.23,24; Pl.15 Figs.7,8)

Synonymy : 1967 Rhabdosphaera pseudomorionum Locker, p.766-767, pl.1, fig.9; pl.2, figs.13,14.

1971 Rhabdolithus pseudomorionum (Locker) Perch-Nielsen, p.51-52, pl.61, figs.20,21.

Occurrence : Middle to Late Eocene of the southern North Sea Basin (NS11-13), Middle Eocene (NP17) of Hampden Beach, New Zealand.

Range : Perch-Nielsen (1985a) - Eocene (Middle).

**Species** : Rhabdosphaera vitrea (Deflandre) Bramlette and Sullivan, 1961.

**Synonymy** : 1954 Rhabdolithus vitreus Deflandre in Deflandre and Fert, p.157, pl.12, figs.28,29; text-figs.83,84.

1961 Rhabdosphaera vitrea (Deflandre) Bramlette and Sullivan, p.147, pl.5, figs.16,17.

See Perch-Nielsen (1971c) for further references.

**Occurrence** : Middle to Late Eocene of the North Sea Basin (NS11-13), Middle Eocene (NP15) of Hampden Beach, New Zealand, and Early Oligocene (NP21) of Alabama.

**Range** : Bybell (1975) - upper Middle Eocene of Alabama and Eocene to Oligocene of many other localities.

**FAMILY** Syracosphaeraceae Lemmermann, 1908

**Genus** Cepekiella Roth, 1970

**Type species** : C. elongata Roth, 1970.

**Species** : Cepekiella lumina (Sullivan) Bybell, 1975.

**Synonymy** : 1965 Cyclococcolithus luminus Sullivan, p.33, pl.3, fig.9a,b.

1975 Cepekiella lumina (Sullivan) Bybell, p.236, pl.5, figs.5,6.

See Bybell (1975) for further references.

**Occurrence** : Middle Eocene and Miocene of the North Sea Basin (NS6, 11-14).

**Range** : Bybell (1975) - Middle Eocene of Alabama and Eocene to Oligocene of many other localities.

**Genus** Syracosphaera Lohmann, 1902

**Type species** : S. pulchra Lohmann, 1902 ex Loeblich and Tappan, 1963.

**Species** : Syracosphaera histrica Kamptner, 1941.

(Pl.11 Fig.22)

Synonymy : 1941 *Syracosphaera histrica* Kamptner, p.84, pl.6, figs.65-68.

Occurrence : Miocene of the North Sea Basin (NS2-4).

Range : Sachs and Skinner (1973) - Pliocene and Pleistocene of Louisiana continental shelf.

FAMILY **Calyptrosphaeraceae** Boudreaux and Hay, 1969

Genus *Clathrolithus* Deflandre *in* Deflandre and Fert, 1954

Type species : *C. ellipticus* Deflandre *in* Deflandre and Fert, 1954.

Species : *Clathrolithus spinosus* Martini, 1961.

(Pl.D. Figs.11,12; Pl.14 Fig.17)

Synonymy : 1961 *Clathrolithus spinosus* Martini, p.19, pl.4, fig.38.

See Perch-Nielsen (1971c) for further references.

Occurrence : Middle to Late Eocene of 49/9-1 (NS11-13).

Range : Perch-Nielsen (1985a) - Late Eocene.

Genus *Corannulus* Stradner, 1962

Type species : *Corannulus germanicus* Stradner, 1962.

Species : *Corannulus germanicus* Stradner, 1962.

(Pl.13 Figs.13,14)

Synonymy : 1962 *Corannulus germanicus* Stradner, p.366, pl.1, figs.21-30.

See Perch-Nielsen (1971c) for further references.

Occurrence : Late Eocene of the North Sea Basin (NS11).

Range : Perch-Nielsen (1985a) - Late Eocene.

Genus *Daktylethra* Gartner *in* Gartner and Bukry, 1969

Type species : *Daktylethra punctulata* Gartner *in* Gartner and Bukry, 1969.

Species : *Daktylethra punctulata* Gartner *in* Gartner and Bukry, 1969.

(Pl.4 Fig.14)

**Synonymy** : 1969 Daktylethra punctulata Gartner in Gartner and Bukry, pl.141, figs.1-3; pl.142, fig.10.

See Bybell (1975) for further references.

**Occurrence** : Middle to Late Eocene of the North Sea Basin (NS11-14).

**Range** : Bybell (1975) - Middle Eocene of Alabama and Eocene of many other localities.

**Genus** Holodiscolithus Roth, 1970

**Type species** : Discolithus macroporus Deflandre in Deflandre and Fert, 1954.

**Species** : Holodiscolithus macroporus (Deflandre) Roth, 1970.

**Synonymy** : 1954 Discolithus macroporus Deflandre in Deflandre and Fert, p.24, pl.11, fig.5.

1967 Discolithina macroporus (Deflandre) Levin and Joerger, p.167, pl.2, fig.5.

1970 Holodiscolithus macroporus (Deflandre) Roth, p.866-867, pl.11, fig.6.

See Roth (1970) for further references.

**Occurrence** : Late Oligocene and Middle Miocene from the central North Sea Basin (NS3,8).

**Range** : Roth (1970) - Early Oligocene of Alabama, JOIDES Hole 5, and Glimmerode (N. Germany).

**Species** : Holodiscolithus solidus (Deflandre) Roth, 1970.

**Synonymy** : 1954 Discolithus solidus Deflandre in Deflandre and Fert, p.141, pl.12, figs.14-16.

1967 Discolithus solida (Deflandre) Levin and Joerger, p.168, pl.2, figs.12a-c.

1970 Holodiscolithus solidus (Deflandre) Roth, p.867, pl.11, fig.5.

See Roth (1970) for further references.

Occurrence : Late Eocene to Early Oligocene of the North Sea Basin (NS10-11).

Range : Roth (1970) - Early Oligocene of JOIDES Hole 5, Alabama, and Trinidad.

Genus Lanternithus Stradner, 1962

**Type species** : L. minutus Stradner, 1962.

Species : Lanternithus minutus Stradner, 1962.

(Pl.C. Figs.2,6,10; Pl.4 Figs.5,6; Pl.12 Figs.11,12; Pl.14 Fig.21)

Synonymy : 1962 Lanternithus minutus Stradner, p.375-376, pl.2, figs.12-15.

1969 Lanternithus minutus Stradner - Gartner and Bukry, p.1217, pl.139, figs.4-6; pl.142, figs.8,9.

See also Aubry (1988).

Occurrence : Middle Eocene to Middle Oligocene of the North Sea Basin (NS9-13), and in similar age of sediment from many of the other sections studied.

Range : Perch-Nielsen (1985a) - Middle Eocene to Early Oligocene.

Genus Orthozygus Bramlette and Wilcoxon, 1967

**Type species** : Zygolithus aureus Stradner, 1962.

Species : Orthozygus aureus (Stradner) Bramlette and Wilcoxon, 1967.

(Pl.4 Fig.15)

Synonymy : 1962 Zygolithus aureus Stradner, p.368, pl.1, figs.31-36.

1967 Orthozygus aureus (Stradner) Bramlette and Wilcoxon, p.116, pl.9, figs.1-4.

1968 Zygosphaera aurea (Stradner) Stradner and Edwards, pl.44, fig.6.

See Bybell (1975) for further references, and see also Aubry (1988).

**Occurrence** : Late Eocene of 49/10-1 (NS11), and Early Oligocene (NP21) of Alabama.

**Range** : Bybell (1975) - upper Middle Eocene of Alabama and Eocene to Oligocene of many other localities.

**Genus** *Semihololithus* Perch-Nielsen, 1971b

**Type species** : *S. biskayae*, Perch-Nielsen, 1971b.

**Species** : *Semihololithus kerabyi* Perch-Nielsen, 1971b.

**Synonymy** : 1971 *Semihololithus kerabyi* Perch-Nielsen, p.357, pl.9, figs.5-7; pl.10, figs.1-6; pl.14, figs.19-21.

See also Aubry (1988).

**Occurrence** : Late Eocene of 49/9-1 (NS11).

**Range** : Perch-Nielsen (1985a) - Palaeocene.

**Genus** *Zygrhablithus* Deflandre, 1959

**Type species** : *Zygolithus bijugatus*, Deflandre *in* Deflandre and Fert, 1954.

**Species** : *Zygrhablithus bijugatus* (Deflandre) Deflandre, 1959.

(Pl.3 Fig.2; Pl.6 Figs.1-3; Pl.12 Figs.1,2,7,8,22)

**Synonymy** : 1954 *Zygolithus bijugatus* Deflandre *in* Deflandre and Fert, p.148, pl.11, figs.20-21; text-fig.59.

1959 *Zygrhablithus bijugatus* (Deflandre) Deflandre, p.135.

See Bybell (1975) for extensive synonymy.

**Occurrence** : Middle Eocene to Late Oligocene of the North Sea Basin (NS8-14), and in similar age of sediment in many of the other sections studied.

**Range** : Perch-Nielsen (1985a) - Early Eocene to Late Oligocene (NP12-25).

INCERTAE SEDIS

Genus Ellipsolithus Sullivan, 1964

Type species : Coccolithus macellus Bramlette and Sullivan, 1961.

Species : Ellipsolithus macellus (Bramlette and Sullivan) Sullivan, 1964.

Synonymy : 1961 Coccolithus macellus Bramlette and Sullivan, p.152-153, pl.7, figs.11-13a-d.

1964 Ellipsolithus macellus (Bramlette and Sullivan) Sullivan, p.184, pl.5, fig.3a,b.

Occurrence : Early Palaeocene of the North Sea Basin (NS17-18).

Range : Bramlette and Sullivan (1961) - Palaeocene to Early Eocene (rare at top of range) of California, and Palaeocene of Trinidad and Gan in France; Perch-Nielsen (1985a) - Early Palaeocene to Early Eocene (NP4-12).

Genus Imperiaster Martini, 1970

Type species : Discoaster obscurus Martini, 1958.

Species : Imperiaster obscurus (Martini) Martini, 1970.

Synonymy : 1958 Discoaster obscurus Martini, p.358, pl.1, figs.4a-c.

1970 Imperiaster obscurus (Martini) Martini, p.384, pls.1-4.

Occurrence : Early Eocene of 29/7-1 (NS15).

Range : Perch-Nielsen (1985a) - Early Eocene (NP11-12).

Genus Nannotetrina Achutan and Stradner, 1969

Type species : N. fulgens (Stradner) Achutan and Stradner, 1969.

Species : Nannotetrina fulgens (Stradner) Achutan and Stradner, 1969.

(Pl.5 Fig.11)

Synonymy : 1960 Nannotetraster fulgens Stradner, p.268-269, text-figs.10,16.

1969 Nannotetrina fulgens (Stradner) Achutan and Stradner, p.7, pl.5, figs.4-6.

See Romein (1979) for further references.

**Occurrence** : Middle Eocene of the southern North Sea Basin (NS13), Middle Eocene (NP14-16) of the Isle of Wight, and Middle Eocene (NP15) of Hampden Beach, New Zealand

**Range** : Perch-Nielsen (1985a) - Middle Eocene (NP15).

**Species** : Nannotetrina nitida (Martini) Aubry, 1983.

(Pl.7 Fig.5)

**Synonymy** : 1961 Tetralithus nitidus Martini, p.4, pl.1, fig.5; pl.4, fig.41.

1983 Nannotetrina nitida (Martini) Aubry, p.149-150, pl.5, figs.13-14.

**Occurrence** : Middle Eocene (NP14-16) of the Isle of Wight.

**Range** : Aubry (1983) - Middle Eocene (NP15-16).

**Genus** Tribrachiatus (Shamrai) Romein, 1979

**Type species** : Discoaster tribrachiatus Bramlette and Riedel, 1954.

**Species** : Tribrachiatus orthostylus (Bramlette and Riedel) Shamrai, 1963.

(Pl.8 Fig.1; Pl.16 Fig.19)

**Synonymy** : 1954 Discoaster tribrachiatus Bramlette and Riedel, p.397, pl.38, fig.11.

1963 Tribrachiatus orthostylus (Bramlette and Riedel) Shamrai, p.38.

See also Romein (1979) and Aubry (1988) for further references.

**Occurrence** : Early Eocene of the North Sea Basin (NS15), Early Eocene (NP11-12) of the London Clay Formation, North London area.

**Range** : Perch-Nielsen (1985a) - Early Eocene (NP11-12).

Remarks : T. orthostylus consists of a single unit of calcite constructed into a three-armed structure. The termination of each arm may be smooth or slightly notched. The preservation of the study material did not generally allow for such variation to be noted. This species was found to be very distinctive and biostratigraphically useful in dating the Early Eocene assemblages of the North Sea Basin, and the London Clay Formation of onshore sections.

## RETICULOFENESTRA - A CRITICAL REVIEW OF TAXONOMY, STRUCTURE AND EVOLUTION :

### 4.4.1 INTRODUCTION :

In 1966 Hay, Mohler and Wade coined the generic name Reticulofenestra. Since then numerous authors have used and adapted this description in various ways without formal emendation of the original description. The taxonomic significance of such features as central area grill, tube cycle and rim structure is discussed with respect to previously published observations and the author's extensive personal research on Tertiary nannofloras from the North Sea Basin, Cyprus, Indonesia, New Zealand, Alabama, and southern England. A formal emendation of the genus is made together with a comprehensive classification of key Reticulofenestra species. The terminology employed in this classification has been derived from the original type descriptions and supplemented by the author's observations. Scanning electron microscope analysis of reticulofenestrids at various stages of mechanical breakdown has revealed details of the ultrastructure of these forms, complementing SEM,TEM, and LM work previously published. Appreciation of the ultrastructural detail enables comment to be made on possible lines of evolution, both within the genus Reticulofenestra and between members of the family Noelaerhabdaceae.

### 4.4.2 THE GENERIC NAME RETICULOFENESTRA :

In 1966 Hay, Mohler and Wade introduced the generic name Reticulofenestra and defined the genus as follows (p.386):

"Placoliths with a large central opening spanned by a reticulate or lacy net, a tube cycle of tall imbricate wedges is exposed distally, but not proximally, a narrow proximal rim of many thin rays and a wide distal rim of many tubular elements. Type species = R. caucasica Hay, Mohler and Wade 1966".

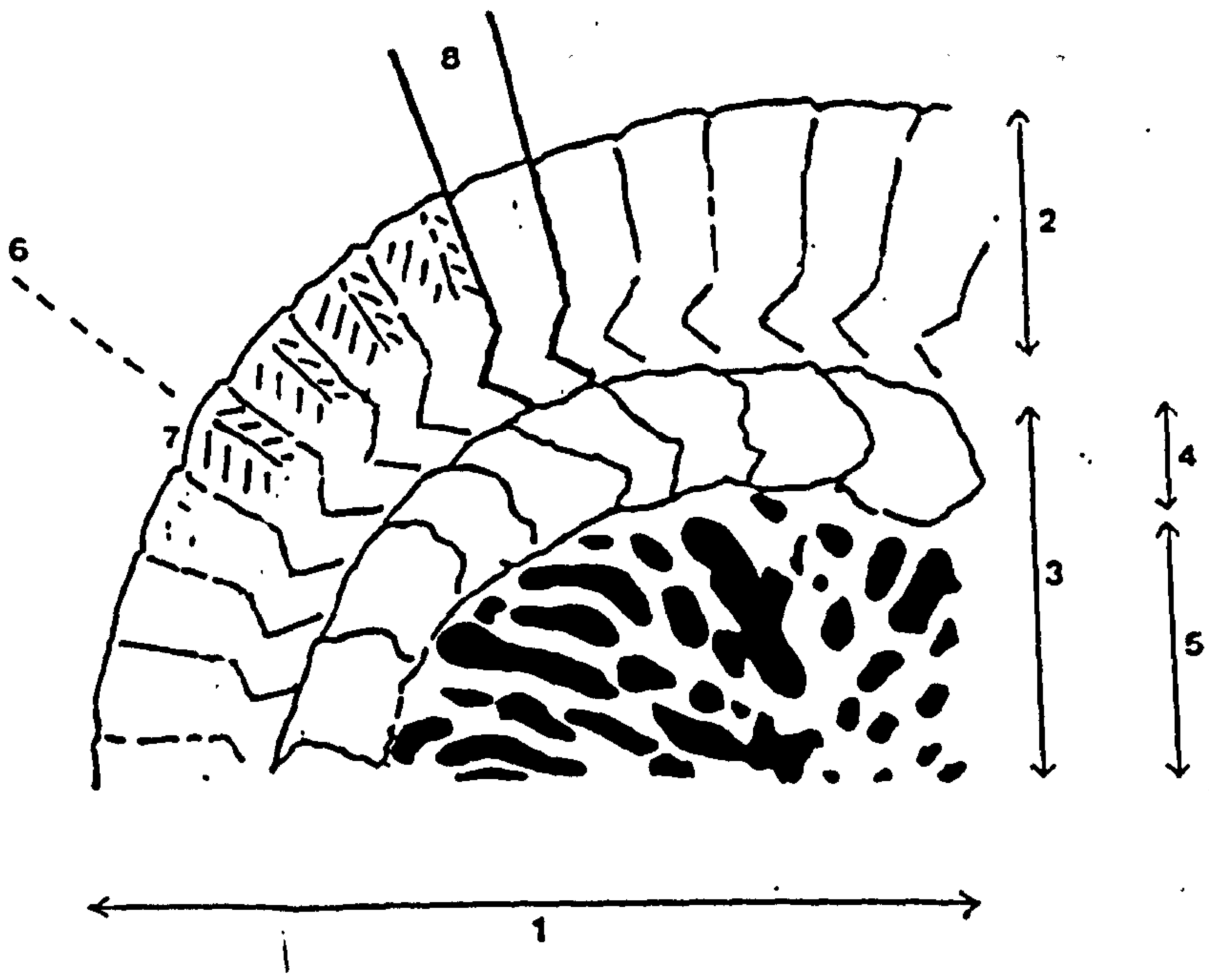
The most important part of this definition, the criterion by which Reticulofenestra species are differentiated from other members of the family Noelaerhabdaceae, is the presence, or evidence of the presence, of a 'lacy net'. A 'tube cycle' is also possessed by the other genera of this family and a 'large central opening' is a very subjective character which certainly does not apply to many accepted species of Reticulofenestra.

Two years later in 1968, Stradner (in Stradner and Edwards, p.19) gave an emended definition of the genus with the important additional observation that the tube cycle could be 'contracted' towards the centre of the ellipse, so forming a "ceiling"-like cover to the central area. Stradner observed that a form with this structure on the distal side had been described by Hay, Möhler and Wade (1966) as a species of Syracosphaera.

Edwards (1973) gave an extremely detailed definition of a species within the genus Reticulofenestra (R. hampdenensis), documenting in particular the complexity of the rim elements. His emended diagnosis of the genus certainly elaborated upon the structure of Reticulofenestra, but utilised fine detail only observable in the most meticulously analysed material (See Fig.40 ) and excluded forms with a 'plugged' central area (e.g. R. scissura and R. callida). Waghorn (1981), however, re-introduced the idea that Reticulofenestra can have a 'plugged' central area via a series of diagrams (see Fig.41), but made no formal emendation of the genus.

FIG. 40.

RETICULOFENESTRA ; ULTRASTRUCTURAL DETAIL




re-drawn and modified from Edwards (1973).

DISTAL VIEW :

1 = Coccolith radius

2 = Distal rim

3 = Central area

4 = Tube cycle

5 = Central area grill

6 = Longitudinal ridge

7 = Chevron ridges

8 = V-shaped sutures

Romein (1979) described Reticulofenestra in great detail based upon Hay, Mohler and Wade's (1966) definition. He highlighted the light microscope characteristics, (op. cit., p.127) but omitted any detailed reference to central area structure.

In 1980 Backman applied statistical analysis to the study of Neogene reticulofenestrids in order to differentiate between very similar species which were found at the same stratigraphical levels. There was no attempt to emend the original generic definition, but criteria for separating species with similar rim and central area characteristics were established.

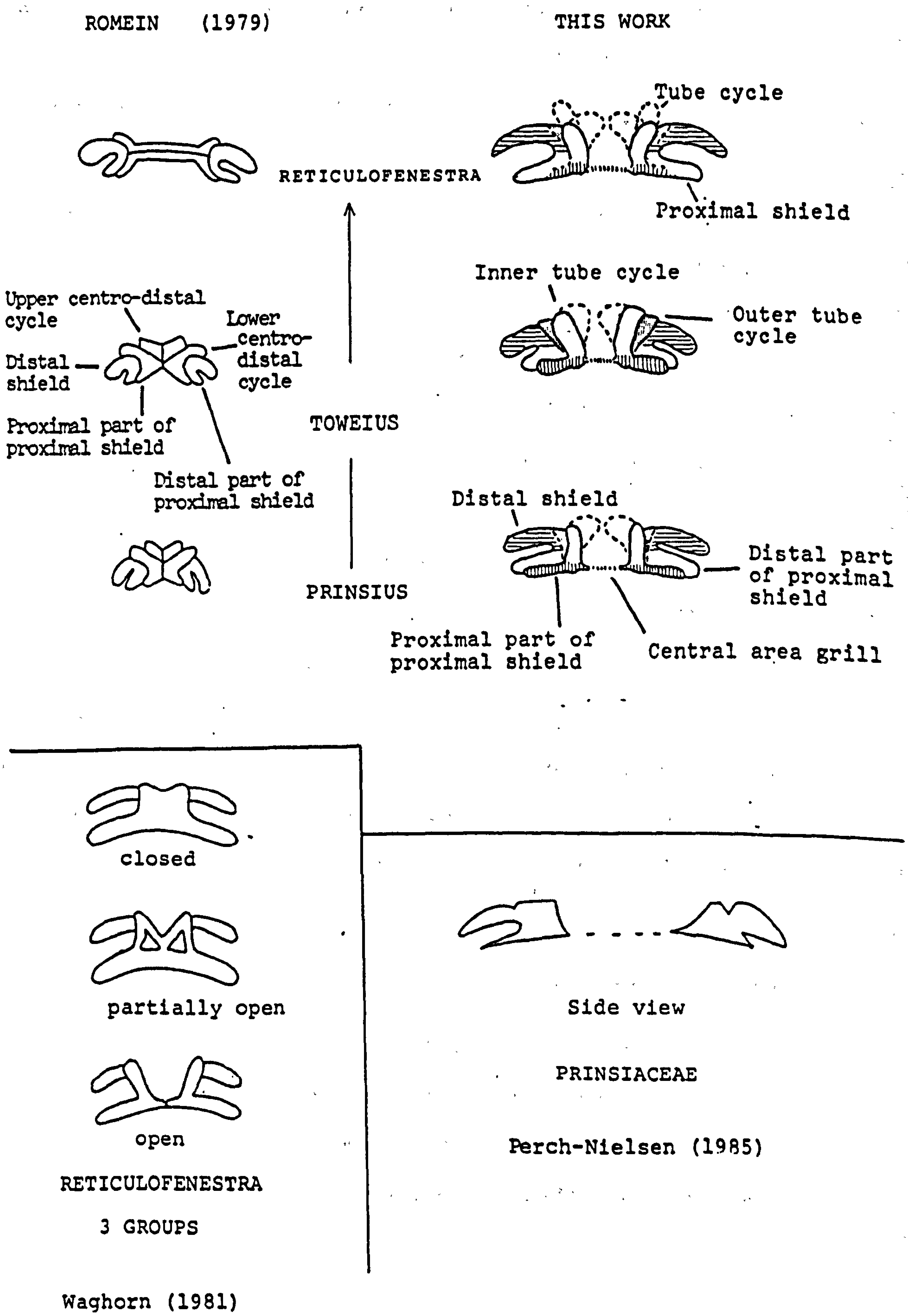
Perch-Nielsen (1985b, p.86) discussed the need to clarify the generic and species concepts of the family Noelaerhabdaceae (= Prinsiaceae; invalid, ICBN Art.37.1) in order that biostratigraphical, ecological and other inferences could be made with a greater degree of confidence.

Backman and Hermelin (1986) re-iterated the problem of species classification and set up rigorous morphometric parameters for their recognition within what was a still loosely defined genus. Most recently Pujos (1987) set out to clarify the taxonomy of 'small and medium'-sized reticulofenestrids, but in isolation from related species and with no clear definition of the genus.

### 4.4.3 ULTRASTRUCTURE AND TAXONOMY :

If a morphological feature is gradational in nature then clearly it cannot be used taxonomically without unequivocal qualitative data. In species placed in Reticulofenestra in the literature, tube cycle and central area characteristics can be seen to be variable or gradational. This aspect of the morphology has been

FIG. 41.


ROMEIN (1979)
THIS WORK
Tube cycle
RETICULOFENESTRA
Proximal shield
Inner tube cycle
Outer tube cycle
Upper centro-distal cycle
Lower centro-distal cycle
Distal shield
Proximal part of proximal shield
TOWEIUS
Distal part of proximal shield
Distal shield
Distal part of proximal shield
PRINSIUS
Proximal part of proximal shield
Central area grill
closed
partially open
open
RETICULOFENESTRA
3 GROUPS
Waghorn (1981)
Side view
PRINSIACEAE
Perch-Nielsen (1985)

repeatedly ignored, and new genera have been erected which might be better considered as Reticulofenestra morphovariants. e.g. Dictyococcites.

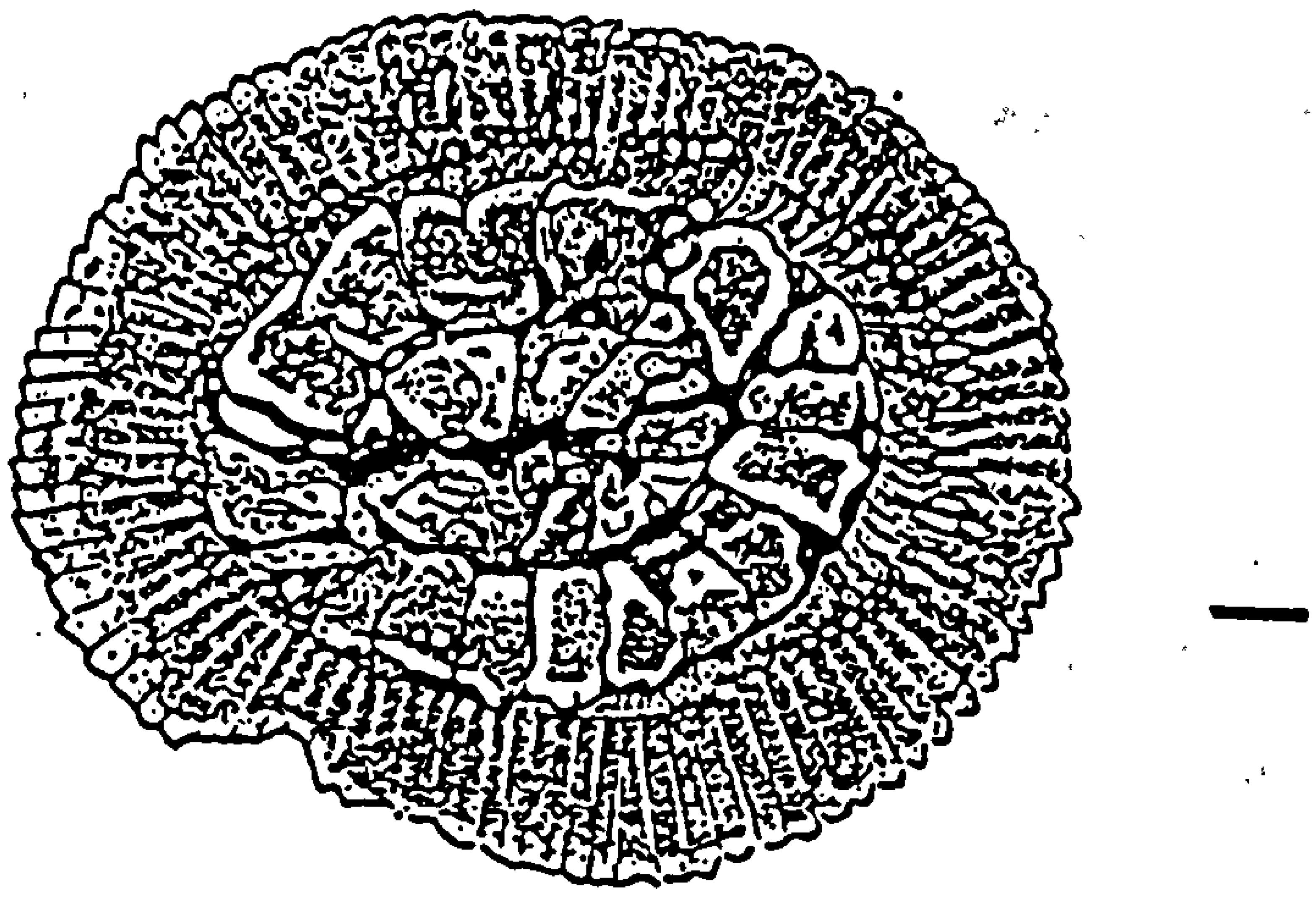
Careful consideration of the ultrastructure of the reticulofenestrid morphotype and of its potential for variation (both in terms of the number of shield elements to the number of central grill elements, and of central grill architecture), provides a working definition from which coherent, unambiguous species descriptions can be derived. The majority of workers have, however, continued to follow the original definition of Hay, Mohler and Wade (1966) despite the observations of Stradner (in Stradner and Edwards 1968) which suggest the possibility of various ratios of shield width to central area grill width, and the observations of Waghorn (1981) illustrating the potential for central area grill variation. New genera have been erected when deviations from the type description have been noted. Perch-Nielsen (1971c, p.30-31), for example, described several species of Reticulofenestra, but also erected the new genus Cribrocentrum for forms in which every second element of the shield contributed to the distally projecting central grill. This can be interpreted as being synonymous with the "group 3" Reticulofenestra of Stradner (in Stradner and Edwards 1968, text fig. 21) and the "partially closed" Reticulofenestra of Waghorn (1981), and could be included in Reticulofenestra on the basis of Edwards' (1973) emended definition. The generic names Cribrocentrum and Dictyococcites are therefore considered superfluous as they are defined solely upon changes in the central area structure. On this basis, these particular changes should only have a species level ranking.

Bown (1987) recently demonstrated that consistent rim structures are diagnostic features at family level. The family Noelaerhabdaceae (Jerkovič 1970) is certainly characterised by a consistent rim structure, and therefore represents a

RETICULOFENESTRA : PRESERVATIONAL VARIATION

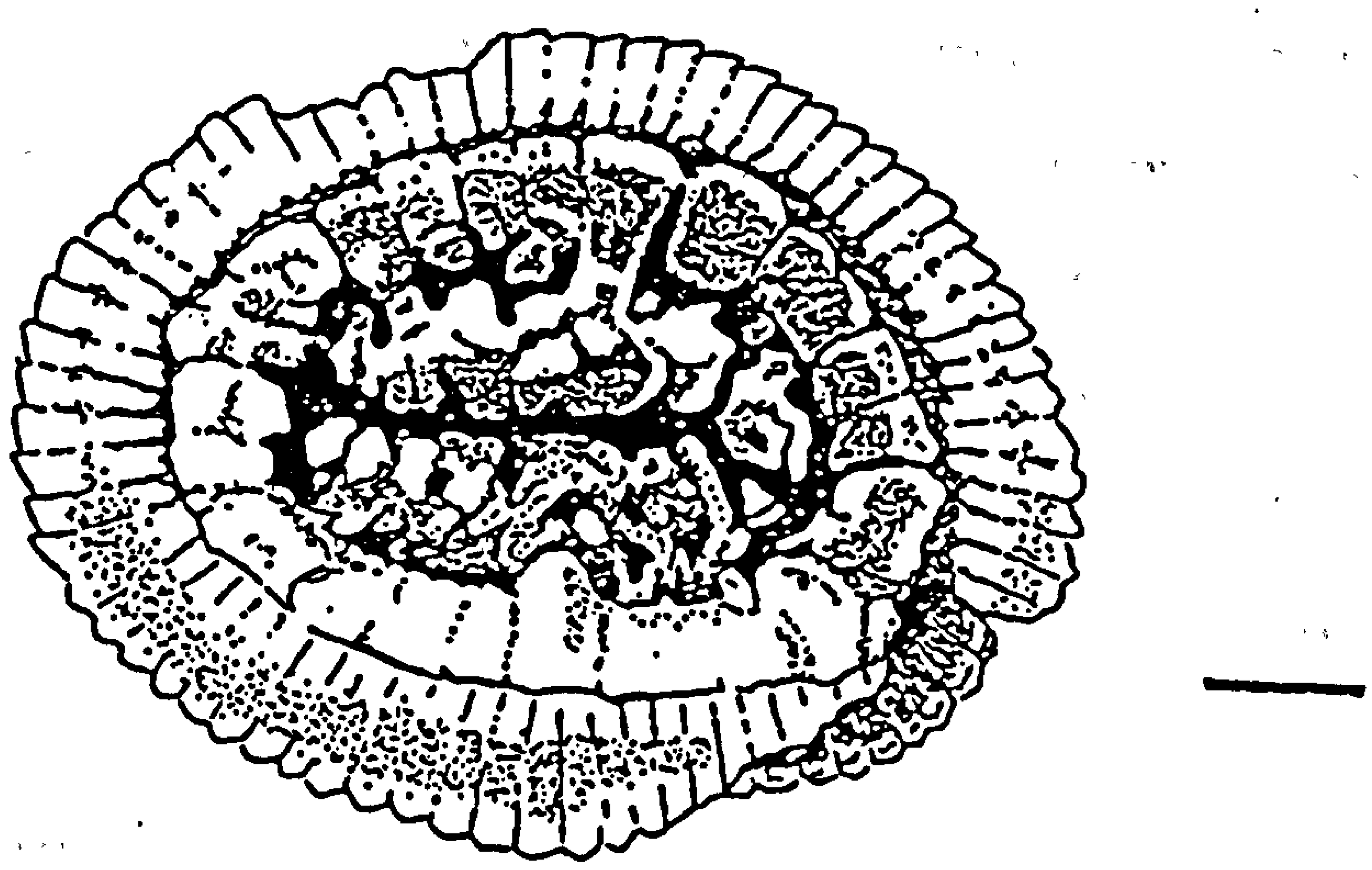
FIG. 42

A



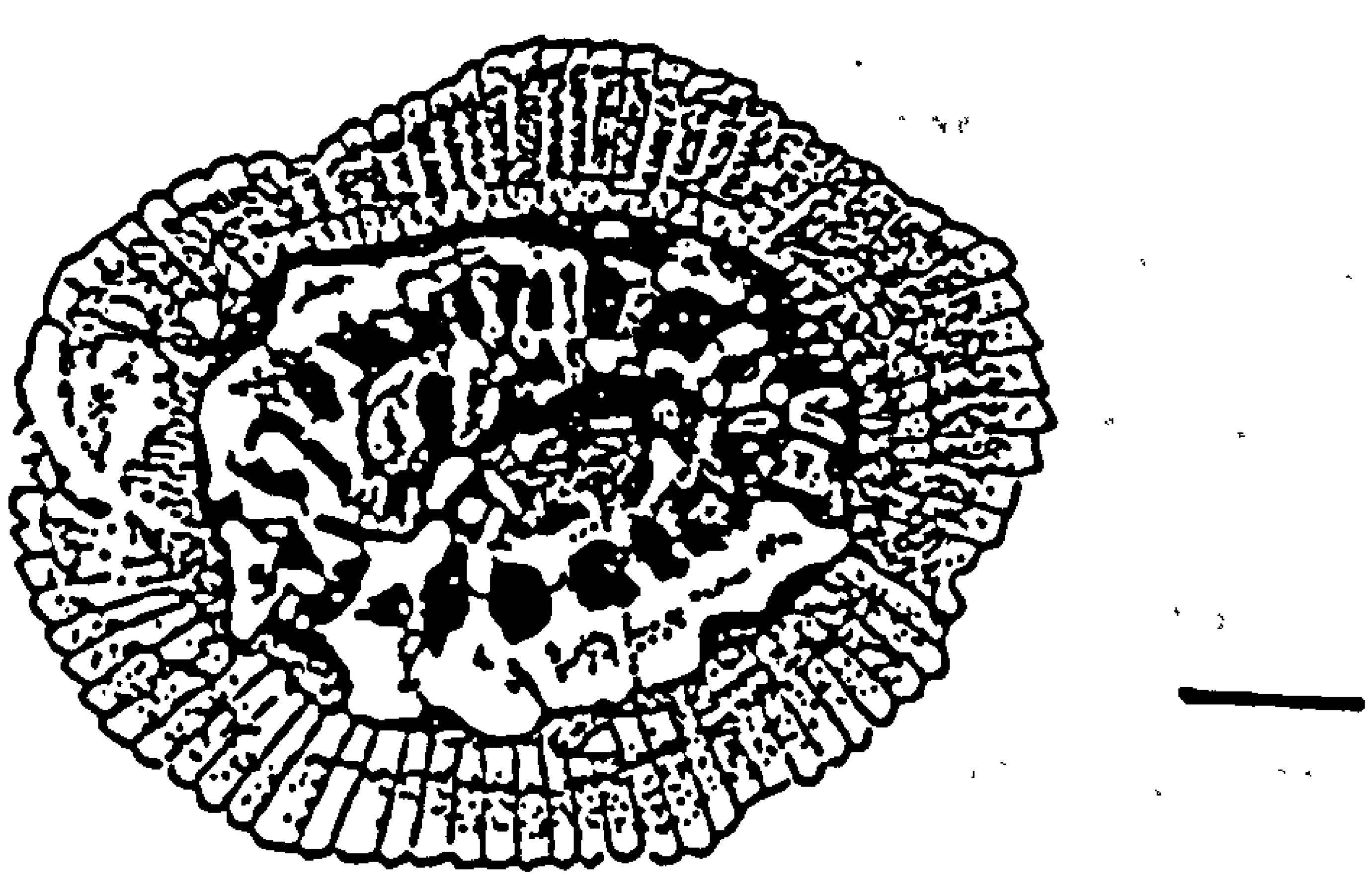
Reticulofenestra scissura : Overgrown tube cycle and central area grill. UCL - 2216 - 05 X 6875

B



Reticulofenestra foveolata : Well preserved tube cycle, slightly overgrown central area grill. UCL- 2349-33 X 14375

C



Reticulofenestra foveolata : Etched tube cycle and central area grill. UCL - 2335-18 X14375 clear taxonomic grouping. Changes in the detail of the rim structure are used to define genera within a family, as has been done for the Noelaerhabdaceae, but central area characteristics may occur repeatedly in spatially and temporally disjunct forms and thus are not used for classification above the species level.

The nature of the reticulate grill which covers the central opening is considered here to be a feature reflecting the species level. This opinion has been a matter of debate by previous authors. Stradner (in Stradner and Edwards 1968) recognised three groups of Reticulofenestra based upon shield width to central area grill width ratios, but made no taxonomic inferences other than to suggest that the reticulate net may vary within the genus. Similarly, Waghorn (1981) illustrated three groups of Reticulofenestra based upon central area structure, but again no taxonomic conclusions were drawn.

In contrast Haq (1968) and Perch-Nielsen (1971c) described new genera, Stradnerius and Cribrocentrum respectively, on the basis of deviations from the central area characteristics of the type species of Reticulofenestra. Haq (1971) stated that 'plugging' of the central area grill is an extension of crystal growth within the reticulate structure and not, therefore, of taxonomic value at generic level. Haq (op. cit., p.72) also noted that types of reticulate structure, previously attributed to diagenetic changes, occurred consistently in samples from many different areas with different states of preservation, and so were of taxonomic value at specific level (see Fig.42 for examples from North Sea study material). If the effects of preservation are not considered, conspecific specimens may easily be interpreted as separate species.

The structure of Noelaerhabdaceae forms in cross-section has been illustrated previously by Romein (1979, fig. 38) in his evolutionary lineage and by Perch-Nielsen (1985a, fig. 56 as Prinsiaceae) in an overview of the family (see Fig.41).

The reconstructions of Romein (op. cit.) are unfortunately inaccurate in a number of important details, whilst Perch-Nielsen's diagram is a simple compilation to show terminology for the Noelaerhabdaceae.

Young (1987, fig.12) produced schematic cross-sections for many Neogene species, including the various morphotypes of Reticulofenestra, and also presented a diagram of a single reticulofenestrid element (op. cit., fig.11) which accurately illustrated the interdependent relationships of the ultrastructural components.

By examining broken and etched specimens in the scanning electron microscope it has been possible to elucidate the nature of the cross-section in reticulofenestrid coccoliths. A gradational change is seen in the structure of the coccolith from Prinsius to Toweius to Reticulofenestra, the crucial developments of which involved changes in the proximal shield and the tube cycle (see Fig.41). In Prinsius and Toweius Romein (1979, fig.38) considered the "upper centro-distal cycle" to lie as a 'crown' on top of the "lower centro-distal cycle", which is an extension of the proximal shield. However, by tracing the tube cycle development through Prinsius and Toweius to Reticulofenestra it is clear that the inner tube cycle (= "upper centro-distal cycle") is a projection of the proximal shield, whilst the outer tube cycle (= "lower centro-distal cycle") fuses with the elements of the shields (see Fig.41). The representation of the central area grill as 'doubled' (in R. dictyoda and R. umbilicus) by Romein (op. cit., fig.38) is an attempt to produce a structure from the "upper centro-distal cycle" (of Toweius) which would otherwise have to be lost. Scanning electron microscopy has revealed that the proximal shield is not doubled in Reticulofenestra, as it is in Toweius and Prinsius; micrographs of reticulofenestrids which do show separation of the proximal shield (e.g. Perch-Nielsen, 1972, pl.7, fig.5) are considered to be of slightly etched specimens of Toweius, not Reticulofenestra.

Theodoridis (1984) erected two new species of Reticulofenestra, using the original diagnosis of Hay, Mohler and Wade (1966) as a basis for identification. He also considered the generic name Cyclicargolithus to be a junior synonym of Reticulofenestra. The type description of Cyclicargolithus clearly states that an open central area must be present, whereas the type description of Reticulofenestra (and emendations) states that a central area grill must be present. The lack of a central area structure of any kind is clearly a characteristic worthy of generic status, as opposed to refinements of a central area structure (e.g. Cribrocentrum) which are not. Both R. rotaria and R. ampliumbilicus must, therefore be assigned to Cyclicargolithus, together with R. floridana.

### 4.4.4 SYSTEMATIC CLASSIFICATION :

**Family** : Noelaerhabdaceae Jerkovič 1970

**Genus** : Reticulofenestra Hay, Mohler & Wade 1966 emend.

**Type species** : Reticulofenestra umbilicus (Levin 1965) Martini & Ritzkowski 1968. (Synonymy: R. caucasica Hay, Mohler & Wade 1966).

**Emended Diagnosis** : Elliptical to circular placoliths in which the central area contains a grill of variable geometry and a central area tube cycle. Both proximal and distal shields are bright under crossed- polarised light, with strongly curved extinction lines, and the distal shield elements are imbricated.

**Description** : Placoliths, circular to elliptical in outline and concavo-convex in side view, consisting of two appressed shields (structurally a single unit including the tube cycle) and a central opening spanned by a reticulate grill of variable geometry. The proximal shield contains a number of radial to slightly imbricated segments which are extended in a variety of combinations into the central opening to form the central grill and are projected distally to form the tube cycle which lines the margin of the central area and abuts the elements of the distal shield. The distal shield consists of wedge-shaped, imbricated laths separated by oblique sutures which are sharply kinked adjacent to the tube cycle. Projection of the tube cycle can give the central area a closed appearance and differential crystal arrangement or multi-layering of the elements may give the central grill a doubled or 'plugged' appearance (see Figs.41 and 42).

Synonymy : 1966 Apertapetra Hay, Mohler and Wade.

Type species = A. samodurovii Hay, Mohler and Wade, p.388, pl.6, figs.1-7.

The description of the type species is largely that for R. caucasica which has page priority over it.

1967 Dictyococcites Black.

Type species = D. danicus Black, p.141, fig.2.

The type description applies to forms which can be adequately accommodated in the genus Reticulofenestra.

1968 Stradnerius Haq.

Type species = S. dictyodus (Deflandre and Fert 1954) Haq, p.31, pl.2, figs.5-8; pl.3, figs.1,2,4-8; pl.4, figs.3,6.

Haq (1971) re-combined this genus into Reticulofenestra, noting that the thickness of the reticulate membrane was a function of crystal arrangement on the inner wall of the central opening, not a feature of taxonomic value.

1971 Cribrocentrum Perch-Nielsen.

Type species = C. foveolatum (Reinhardt 1966) Perch-Nielsen, p.26-27, pl.19, figs.6,7.

Differentiated by a more arched and slightly differently constructed central area grill = characteristics of species level value only.

non 1980 Crenalithus (Roth) Backman.

Type species = C. doronicoides (Black and Barnes) Roth, p.731, pl.3, fig.3.

This generic name is probably synonymous with Cyclicargolithus, the type species of which has an open central area and a tube cycle surrounding the central opening, and not Reticulofenestra as suggested by Backman (1980, p.56-58) in which a central area 'grill' must exist.

The following lists contain only a selection of synonymies for each species :

Species : Reticulofenestra callida (Perch-Nielsen) Bybell, 1975.

(Pl.4 Fig.13; Pl.15 Figs.17,18; Pl.i Fig.9; Pl.ii Figs.17,18)

Synonymy : 1971 Dictyococcites callidus Perch-Nielsen, p.28-29, pl.22, figs.1-4; pl.23, fig.3; pl.61, figs.30-31.

1971 Reticulofenestra scissura Hay, Mohler and Wade - Haq (pro parte) pl.15, figs.2-4; non pl.15, figs.5,6.

1975 Reticulofenestra callida (Perch-Nielsen) Bybell, p.197, pl.21, fig.8.

1981 Reticulofenestra callida (Perch-Nielsen) Waghorn, p.52-53, pl.7, fig.5; pl.8, fig.5; pl.10, fig.2.

**Occurrence :** Middle Eocene to Late Oligocene of the North Sea Basin (NS8-13), Middle Eocene (NP14-16) of the Isle of Wight, Early Oligocene (NP21) of JOIDES Hole 5, and Late Eocene to Early Oligocene (NP20-21) of Alabama.

**Range** : Bybell (1975) - upper Middle Eocene of Alabama and the Eocene and Oligocene of other sections.

**Species** : Reticulofenestra clatrata Müller, 1970b.

**Synonymy** : 1970 Reticulofenestra clatrata Müller, p.116, pl.6, figs.3-5; pl.7, fig.4.

**Range** : Müller (1970) - Middle Oligocene (NP23) of Germany.

**Species** : Reticulofenestra coenura (Reinhardt) Roth, 1970.

**Synonymy** : 1966 Coccolithus coenurus Reinhardt, p.516-517, pl.1, fig.7, text-fig.6.

1968 Reticulofenestra dictyoda (Deflandre and Fert) Hay, Mohler and Wade - Stradner in Stradner and Edwards, (pro parte) p.19-20, pl.12, fig.4; pl.14, fig.1, non pl.12, figs.1-3; pl.13, figs.1,2; pl.14, figs.2-5.

1970 Reticulofenestra coenura (Reinhardt) Roth, p.847.

1971 Cribrocentrum coenurum (Reinhardt) Perch-Nielsen, p.26, pl.21, figs.1-6.

1971 Reticulofenestra coenura (Reinhardt) Haq, p.72, pl.1, figs.10,11.

1973 Reticulofenestra hampdenensis Edwards, (pro parte) p.80-86, figs.38-43,47-53,58-69, non figs.44-46,54-57.

1973 Reticulofenestra coenura (Reinhardt) Roth - Roth, p.732.

1974 Reticulofenestra coenura (Reinhardt) Roth - Sherwood, p.28-29, pl.3, figs.11,12.

1976 Reticulofenestra coenura (Reinhardt) Haq and Lohmann, pl.1, figs.2,3.

1981 Reticulofenestra coenura (Reinhardt) Roth - Waghorn, p.53-54, pl.9, figs.4-8; pl.11, figs.1-7.

**Occurrence** : Middle Eocene to Late Oligocene of the North Sea Basin (NS8-14), Middle to Late Eocene (NP15-19) of Hampden Beach, New Zealand, Middle

Eocene (NP14-16) of the Isle of Wight, Late Eocene (NP20) of William's Bluff, New Zealand, Late Oligocene (NP24) of the South Atlantic Ocean (DSDP-36-329-29-1, 138-139cm and DSDP-36-329-30-2, 132-133cm) and Late Oligocene (NP24) of the Hatton-Rockall Basin (DSDP-12-117-2-3, 147-148cm).

**Range** : Waghorn (1981) - Middle Eocene to Middle Oligocene world-wide.

**Species** : Reticulofenestra daviesii (Haq) Haq, 1971.

(Pl.3 Fig.12; Pl.4 Fig.11; Pl.12 Figs.15,16; Pl.i Fig.6; Pl.ii Figs.13,14)

**Synonymy** : 1968 Stradnerius daviesii Haq, p.32, pl.4, figs.4,5.

1968 Stradnerius dictyodus (Deflandre and Fert) Haq, (pro parte) p.31-32, pl.2, figs.5,6; pl.3, fig.1; pl.4, figs.3-6, non pl.2, figs.7,8; pl.3, figs.2,4-8.

1971 Reticulofenestra daviesii (Haq) Haq, p.73.

1971 Dictyococcites daviesii (Haq) Perch-Nielsen, p.29, pl.20, figs.1,2.

1980 Reticulofenestra daviesii (Haq) Haq - Backman, p.58, pl.6, figs.6-9.

1981 Reticulofenestra daviesii (Haq) Haq - Waghorn, p.57, pl.8, figs.1-4; pl.9, figs.1-3; pl.10, figs.1,3.

**Occurrence** : Middle Eocene and Late Oligocene of the North Sea Basin (NS8,13), and Middle Eocene (NP15) of Hampden Beach, New Zealand.

**Range** : Waghorn (1981) - late Middle Eocene to Middle Oligocene world-wide.

**Species** : Reticulofenestra dictyoda (Deflandre and Fert) Haq, 1971.

(Pl.A. Fig.16,20,24; Pl.ii Fig.8)

**Synonymy** : 1954 Discolithus dictyodus Deflandre and Fert, (pro parte) p.140-141, text-fig.15, non text-fig.16.

1962 Cyclococcolithus dictyodus (Deflandre and Fert) Hay and Towe, p.503, pl.5, fig.4; pl.7, fig.1.

non 1966 Cyclococcolithus dictyodus (Deflandre and Fert) Hay and Towe - Haq, p.31, pl.2, figs.2,5; pl.6, figs.2-6.

non 1968 Stradnerius dictyodus (Deflandre and Fert) Haq, p.31, pl.2, figs.5-8; pl.3, figs.1,2,4-8; pl.4, figs.3,6.

non 1968 Reticulofenestra dictyoda (Deflandre and Fert) Stradner in Stradner and Edwards, p.19, pl.12; pl.13; pl.14; pl.22, fig.4.

1971 Reticulofenestra dictyoda (Deflandre and Fert) Haq, p.73.

1971 Reticulofenestra dictyoda (Deflandre and Fert) Stradner - Perch-Nielsen, p.30, pl.25, figs.1-3.

1971 Toweius callosus Perch-Nielsen, (pro parte) p.31, pl.61, figs.32,33, non pl.17, figs.3,5; pl.18, fig.5.

1973 Reticulofenestra dictyoda (Deflandre and Fert) Stradner - Edwards, pl.10, figs.5,6.

1979 Reticulofenestra dictyoda (Deflandre and Fert) Stradner - Romein, p.128, pl.4, fig.6.

1983 Reticulofenestra dictyoda (Deflandre and Fert) Stradner - Aubry, p.148, pl.8, fig.24.

Occurrence : Eocene of the North Sea Basin (NS11-15), Middle Eocene (NP14-16) of the Isle of Wight, and Middle Eocene (NP15-17) of Hampden Beach, New Zealand.

Range : Perch-Nielsen (1985a) - Early to Middle Eocene (NP13-16); Waghorn (1981) - early Middle Eocene to middle Late Eocene.

Species : Reticulofenestra foveolata (Reinhardt) Roth, 1970.

(Pl.12 Figs.13,14; Pl.I Fig.10,12)

Synonymy : 1966 Coccolithus foveolatus Reinhardt, p.517, pl.1, fig.14.

1967 Reticulofenestra insignita Roth and Hay in Hay et al., p.449, pl.7, figs.2,3.

1968 Reticulofenestra dictyoda (Deflandre and Fert) Stradner in Stradner and Edwards, (pro parte) pl.12, fig.2; pl.14, fig.1, non pl.12, figs.1,3,4.

1970 Reticulofenestra alabamensis Roth, p.846-847, pl.3, figs.4,5.

1970 Reticulofenestra foveolata (Reinhardt) Roth, p.848.

1970 Reticulofenestra pectinata Roth, p.851, pl.5, fig.1.

1971 Reticulofenestra foveolata (Reinhardt) Haq, p.111, pl.13, figs.7,8; pl.20, figs.1,2.

1971 Cribrocentrum foveolatum (Reinhardt) Perch-Nielsen, p.26-27, pl.19, figs.6,7.

1981 Reticulofenestra alabamensis Roth - Waghorn, p.51, pl.7, figs.1-4.

**Occurrence :** Middle Eocene to Late Oligocene of the North Sea Basin (NS8-14), Late Eocene to Early Oligocene (NP20-21) of Alabama, Middle to Late Eocene (NP15-19) of Hampden Beach, New Zealand, and Late Eocene (NP20) of William's Bluff, New Zealand.

**Range :** Roth (1970) - Late Eocene to Early Oligocene (C. margartiae Zone).

**Species :** Reticulofenestra gabrielae Roth, 1970.

**Synonymy :** 1970 Reticulofenestra gabrielae Roth, p.848, pl.4, fig.1.

**Range :** Roth (1970) - Early Oligocene of JOIDES Hole 5 (E. subdisticha Zone to lower C. margaritae Zone) and Alabama (upper E. subdisticha Zone).

**Species :** Reticulofenestra gartneri Roth and Hay, in Hay et al., 1967.

**Synonymy :** 1967 Reticulofenestra gartneri Roth and Hay, in Hay et al., p.449, pl.7, fig.1.

1981 Reticulofenestra gartneri Roth and Hay - Stradner and Allram, pl.3, figs.1-3.

1984 Reticulofenestra gartneri Roth and Hay - Steinmetz and Stradner, pl.9, fig.8.

**Occurrence** : Late Oligocene to Middle Miocene of the North Sea Basin (NS3,5-8).

**Range** : Hay et al. (1967) - Early Oligocene (up to the R. laevis Zone) of JOIDES Hole 5.

**Species** : Reticulofenestra hesslandii (Haq) Roth, 1970.

**Synonymy** : 1966 Ericsonia hesslandii Haq, p.32-33, pl.1, fig.6; pl.3, fig.1; pl.4, fig.3; pl.5, figs.3-5.

1970 Reticulofenestra hesslandii (Haq) Roth, p.849, pl.4, figs.3,5.

1971 Prinsius hesslandii (Haq) Haq, p.77, pl.2, fig.6.

1976 Dictyococcites hesslandii (Haq) Haq and Lohmann, p.183.

1980 Dictyococcites hesslandii (Haq) Haq and Lohmann - Backman, p.50, pl.5, fig.10.

1981 Reticulofenestra hesslandii (Haq) Roth - Waghorn, p.60-61, pl.14, figs.4-8.

**Range** : Waghorn (1981) - Late Eocene to Oligocene.

**Species** : Reticulofenestra hillae Bukry and Percival, 1971.

(Pl.i Figs.7,13)

**Synonymy** : 1971 Reticulofenestra hillae Bukry and Percival, p.136, pl.6, figs.1-3.

1973 Reticulofenestra hillae Bukry and Percival - Roth, p.732.

1975 Reticulofenestra hillae Bukry and Percival - Bybell, p.197, pl.15, fig.4.

1981 Reticulofenestra hillae Bukry and Percival - Waghorn, p.61-62, pl.15, fig.6.

**Occurrence** : Middle Eocene to Early Oligocene of the North Sea Basin (NS9-13), Late Eocene (NP20) of William's Bluff, New Zealand, Middle to Late Eocene (NP14-16,19) of the Isle of Wight, and Middle Eocene (NP15-17) of Hampden Beach, New Zealand.

**Range** : Bybell (1975) - Eocene/Oligocene of the Atlantic, Pacific and Gulf Coast, and upper Middle Eocene of Alabama; Waghorn (1981) - Late Eocene to Early Oligocene world-wide.

**Species** : Reticulofenestra laevis Roth and Hay in Hay et al., 1967.

(Pl.ii Figs.15,16)

**Synonymy** : 1967 Reticulofenestra laevis Roth and Hay in Hay et al., p.449, pl.7, fig.11.

1970 Reticulofenestra laevis Roth and Hay - Roth, p.850, pl.5, fig.5.

**Occurrence** : Early Oligocene (NP21) of Alabama.

**Range** : Roth (1970) - R. laevis Zone to the middle of the S.distentus-ciperoensis Zone in Oligocene sections on both sides of the Atlantic.

**Species** : Reticulofenestra lockeri Müller, 1970b.

**Synonymy** : 1970 Reticulofenestra lockeri Müller, p.116, pl.6, figs.3-5.

1984 Reticulofenestra lockeri Müller - Baldi-Beke, p.144, pl.14, figs.3-7; pl.38, figs.5-8.

**Range** : Müller (1970) - Middle Oligocene (S. predistentus Zone, NP23, and S. distentus Zone, NP24) of Germany.

**Species** : Reticulofenestra minuta Roth, 1970.

(Pl.1 Fig.14; Pl.l Fig.14)

**Synonymy** : 1970 Reticulofenestra minuta Roth, p.850-851, pl.5, figs.3,4.

1980 Reticulofenestra minuta Roth - Backman, p.58-59, pl.7, figs.1-3.

1981 Reticulofenestra minuta Roth - Waghorn, p.63, pl.27, figs.4,5,7,8.

**Occurrence** : Early Eocene to Pliocene of the North Sea Basin (NS1-15), and in similar age of sediment in many of the other sections studied.

**Range** : Waghorn (1981) - Late Eocene to Middle Oligocene; Perch-Nielsen (1985a) - Late Eocene to Middle Oligocene. See compendium for more complete age range.

**Species** : Reticulofenestra minutula (Gartner) Haq and Berggren, 1978.

**Synonymy** : 1967 Coccolithus minutulus Gartner, p.3, pl.5, figs.3-5.

1978 Reticulofenestra minutula (Gartner) Haq and Berggren, p.1190.

1978 Reticulofenestra haqii Backman, p.110-111, pl.1, figs.1-4.

1980 Reticulofenestra minutula (Gartner) Haq and Berggren - Backman, p.59, pl.7, figs.4,5,8-13.

**Occurrence** : Miocene to Pliocene of the North Sea Basin (NS1-7).

**Range** : Backman (1980) - Miocene.

**Species** : Reticulofenestra oamaruensis (Deflandre in Deflandre and Fert) Stradner in Stradner and Edwards (1968).

**Synonymy** : 1954 Discolithus oamaruensis Deflandre in Deflandre and Fert, p.139, pl.12, figs.1,2.

1967 Discolithina oamaruensis (Deflandre) Levin and Joerger, p.167, pl.2, fig.1a,b.

1968 Reticulofenestra oamaruensis (Deflandre) Stradner in Stradner and Edwards, p.21-22, pl.16-18, text-fig.2B.

**Occurrence** : Late Eocene of 21/11-1 (NS11), Late Eocene (NP20) of William's Bluff, New Zealand, and Early Oligocene (NP21) of Alabama.

**Range** : Waghorn (1981) - Late Eocene and restricted Early Oligocene distribution world-wide.

**Species** : Reticulofenestra onusta (Perch-Nielsen) Wise, 1983.

(Pl.B Figs.14,18,22)

**Synonymy** : 1971 Dictyococcites onustus Perch-Nielsen, p.29, pl.20, figs.3,4; pl.61, figs.28,29.

1983 Reticulofenestra onusta (Perch-Nielsen) Wise, p.505, pl.5, figs.8-9.

**Occurrence** : Middle to Late Eocene of the North Sea Basin (NS11,13).

**Range** : Perch-Nielsen (1985a) - Middle Eocene (NP16).

**Species** : Reticulofenestra perplexa (Burns) Wise, 1983.

**Synonymy** : 1975 Dictyococcites perplexa Burns, p.594, figs.13,19,20.

1976 Dictyococcites antarcticus Haq, p.190.

1980 Dictyococcites antarcticus Haq - Backman, pl.4, figs.4,5.

1983 Reticulofenestra perplexa (Burns) Wise, p.505-506.

1987 Dictyococcites perplexus Burns - Pujos, p.249, pl.1, figs.26-29; text-fig.10.

**Occurrence** : Miocene to Pliocene of the North Sea Basin (NS1-7).

**Range** : Backman (1980) - Miocene of the Hatton-Rockall Basin.

Species : Reticulofenestra pseudoumbilicus (Gartner) Gartner, 1969a.

(Pl.10 Fig.6; Pl.i Fig.15)

Synonymy : 1967 Coccolithus pseudoumbilicus Gartner, p.4, pl.6, figs.1-4.

1969 Reticulofenestra pseudoumbilica (Gartner) Gartner, p.587-589.

1972 Coccolithus gelidus Geitzenauer, p.405-409, pl.1, figs.1,2,5,6.

1972 Reticulofenestra pseudoumbilica (Gartner) Gartner - Ellis, Lohmann and Wray, p.20, pl.3, figs.1,2.

1977 Reticulofenestra pseudoumbilica (Gartner) Gartner - Wind and Wise (pro parte) pl.2, figs.1,2, non pl.2, fig.3.

1978 Reticulofenestra gelidus (Geitznauer) Backman, p.112, pl.1, figs.7-9.

1984 Reticulofenestra pseudoumbilica (Gartner) Gartner - Steinmetz and Stradner, pl.26; pl.27.

1985 Reticulofenestra gelida (Geitznauer) Perch-Nielsen, p.510.

Occurrence : Miocene of the North Sea Basin (NS2-7).

Range : Perch-Nielsen (1985a) - Middle Miocene to Middle Pliocene (NN7-15).

Species : Reticulofenestra reticulata (Gartner and Smith) Roth in Roth and Theirstein, 1972.

(Pl.ii Figs.11,12)

Synonymy : 1967 Cyclococcolithus reticulatus Gartner and Smith, p.4, pl.5, figs.1-4.

1971 Cribrocentrum reticulatum (Gartner and Smith) Perch-Nielsen, p.28, pl.25, figs.4-9.

1972 Reticulofenestra reticulata (Gartner and Smith) Roth in Roth and Thierstein, p.436.

1972 Cribrocentrum reticulatum (Gartner and Smith) Perch-Nielsen -

Perch-Nielsen, pl.7, fig.5.

**Occurrence :** Middle to Late Eocene of the North Sea Basin (NS11-13), Middle to Late Eocene (NP16-19) of Hampden Beach, New Zealand, and Middle Eocene (NP17) of the Isle of Wight.

**Range :** Perch-Nielsen (1985a) - Middle to Late Eocene (NP16-19).

**Species :** Reticulofenestra scissura Hay, Mohler and Wade, 1966.

(Pl.C. Fig.13,17,21; Pl.3 Fig.5; Pl.i Figs.5,8,11; Pl.ii Figs.9,10)

**Synonymy :** 1966 Reticulofenestra scissura Hay, Mohler and Wade, (pro parte) p.387, pl.5, figs.1-5, non pl.5, fig.6.

1966 Syracosphaera bisecta Hay, Mohler and Wade, p.393, pl.10, figs.1-6.

1967 Coccolithus bisectus (Hay, Mohler and Wade) Bramlette and Wilcoxon, p.102, pl.4, figs.11-13.

1967 Coccolithus cf C. scissurus (Hay, Mohler and Wade) Bramlette and Wilcoxon, p.102-103, pl.4, figs.1,2.

1967 Dictyococcites danicus Black, p.141, fig.2.

1968 Reticulofenestra dictyoda (Deflandre and Fert) Hay, Mohler and Wade - Stradner in Stradner and Edwards, (pro parte) p.19-20, pl.12, figs.3,4; pl.13, figs.1,2; pl.14, figs.2-5; pl.22, fig.4, non pl.12, figs.1,2; pl.14, fig.1.

1970 Reticulofenestra bisecta (Hay, Mohler and Wade) Roth, p.847, p.3, fig.6.

1970 Reticulofenestra danica (Black) Roth, p.848, pl.4, fig.2.

1970 Reticulofenestra ornata Müller, p.116, pl.1, figs.4-6; pl.2, fig.4.

1971 Reticulofenestra scissura Hay, Mohler and Wade - Haq, (pro parte) p.75-76, pl.1, figs.12-14; pl.7, figs.7,8,10; pl.15, figs.5,6; pl.16, fig.6, non pl.3, fig.14; pl.7, fig.9; pl.15, figs.2-4,7.

1971 Reticulofenestra scissura Hay, Mohler and Wade - Gartner, p.112-114.

1973 Reticulofenestra bisecta (Hay, Mohler and Wade) Roth - Roth, p.4, fig.1; pl.7, figs.4,5; pl.9, figs.1,2; pl.10, fig.2.

1975 Reticulofenestra bisecta (Hay, Mohler and Wade) - Bybell, p.197, pl.15, fig.5.

1981 Reticulofenestra danica (Black) Roth - Waghorn, p.55-56, pl.11, fig.8; pl.12, figs.1-8; pl.14, figs.1,2.

1983 Reticulofenestra prebisecta Aubry, p.151, pl.5, figs.5,6; pl.8, fig.15.

1984 Reticulofenestra ornata Müller - Baldi-Beke, p.144-145, pl.15, figs.1-4; pl.16, figs.1-4; pl.17, figs.1-4; pl.18, figs.1-4; pl.39, figs.6,7,10.

1984 Reticulofenestra bisecta (Hay, Mohler and Wade) Roth - Steinmetz and Stradner, pl.28, figs.9,10.

**Occurrence** : Middle Eocene to Late Oligocene of the North Sea Basin (NS8-13), and in sediment of similar age from many of the other sections studied.

**Range** : Waghorn (1981) - early Late Eocene (NP17) to Late Oligocene (NP25) world-wide.

**Species** : Reticulofenestra scrippsae (Bukry and Percival) Roth, 1973.

**Synonymy** : 1971 Dictyococcites scrippsae Bukry and Percival, p.128, pl.2, figs.7,8.

1973 Reticulofenestra scrippsae (Bukry and Percival) Roth, p.732.

**Occurrence** : Middle Eocene to Late Oligocene of the North Sea Basin (NS8-13), and in sediment of a similar age from many of the other sections studied.

**Range** : Waghorn (1981) - late Middle Eocene to Late Oligocene world-wide.

Species : Reticulofenestra umbilicus (Levin) Martini and Ritzkowski, 1968.

(Pl.A. Fig.2,6,10; Pl.4 Fig.7; Pl.5 Fig.5; Pl.i Figs.1-4; Pl.ii Fig.7)

Synonymy : 1962 Coccolithus ?sp. Bouché, p.84, pl.1, fig.21a-c.

1965 Coccolithus umbilicus Levin, p.265, pl.41, fig.2.

1966 Reticulofenestra caucasica Hay, Mohler and Wade, p.386-387, pl.2, figs.5-8; pl.3; pl.4.

1966 Apertapetra samodurovii Hay, Mohler and Wade, p.388, pl.6.

1966 Coccolithus pelycomorphus Reinhardt, p.515-516, pl.1, figs.2-6; text-fig.5.

1967 Apertapetra umbilicus (Levin) Levin and Joerger - Bramlette and Wilcoxon, p.101, pl.5, figs.1,2.

1967 Coccolithus umbilicus Levin - Gartner and Smith, p.3, pl.1, figs.3,4; pl.2, figs.1-3a,b.

1968 Reticulofenestra umbilica (Levin) Martini and Ritzkowski, p.245, pl.1, figs.11,12.

1971 Reticulofenestra umbilica (Levin) Martini and Ritzkowski - Perch-Nielsen, p.30-31, pl.21, fig.7; pl.23, figs.1,2; pl.24, figs.1-3.

1974 Reticulofenestra umbilica (Levin) Martini and Ritzkowski - Sherwood, p.29, pl.3, figs.3,4.

1975 Reticulofenestra caucasica Hay, Mohler and Wade - Hodson and West, p.180-182, text-fig.2.

1976 Reticulofenestra umbilica (Levin) Martini and Ritzkowski - Haq and Lohmann, pl.7, figs.9,12; pl.14, figs.7,8.

1979 Reticulofenestra umbilica (Levin) Martini and Ritzkowski - Romein, p.128-129.

1982 Reticulofenestra tokodensis Báldi-Beke, p.299-301, pls.1-3.

Occurrence : Middle Eocene to Early Oligocene of the North Sea Basin (NS10-

14), Middle to Late Eocene (NP14-16,19) of the Isle of Wight, Late Eocene to Early Oligocene (NP20-21) of Alabama, Late Eocene (NP20) of William's Bluff, New Zealand, and Middle to Late Eocene (NP15-19) of Hampden Beach, New Zealand.

**Range** : Waghorn (1981) - Middle Eocene (NP15) to Early Oligocene (NP22) world-wide.

The following species are here placed in the genus Reticulofenestra Hay, Mohler and Wade emend. :

Species : Reticulofenestra martinii (Hay & Towe, 1962) nov. comb.

Basionym : 1962 Cyathosphaera martinii Hay & Towe, p.510, pl.4, figs.2?,3,4.

Range : Hay and Towe (1962) - Early Eocene.

Species : Reticulofenestra productella (Bukry, 1975) nov. comb.

(Pl.10 Fig.16)

Basionym : 1975 Crenalithus productellus Bukry, p.690.

Synonymy : 1963 Ellipsoplacolithus productus Kamptner, p.172, pl.8, figs.42,44.

1973 Coccolithus productus (Kamptner) Sachs and Skinner, p.138, pl.1, figs.18-21; Table 2, fig.13.

1980 Dictyococcites productus (Kamptner) Backman, p.49-50, pl.4, figs.1-3,6,7.

**Occurrence** : Middle to Late Miocene of the North Sea Basin (NS2-3).

**Range** : Sachs and Skinner (1973) - Pliocene and Pleistocene.

See compendium for full discussion of these species and their synonymy.

### 4.4.5 EVOLUTION :

#### 4.4.5.1 Introduction :

A number of studies have considered aspects of the evolution of reticulofenestrids, either with respect to one species (or more strictly 'morphotype') evolving into another (Backman 1980, Backman and Hermelin 1986) or aspects of the development of the family Noelaerhabdaceae (Romein 1979). However, no attempt has been made to trace the evolutionary links of all Reticulofenestra species, to group them on the basis of their ultrastructure, and to relate the structures within the family Noelaerhabdaceae in a taxonomical sense. The problems of classification within this group are notorious and a matter of dispute. It is probably due to this complexity that no previous attempt has been made to establish a comprehensive evolutionary scheme.

Electronmicrographs and light micrographs were used, in association with published information to classify all species considered to be valid and within the emended definition of Reticulofenestra, and to relate these in an evolutionary framework (Fig.43). Romein (1979, p.72) traced the evolution of the family Noelaerhabdaceae from its inception in the earliest Palaeocene (from Prinsius petalosus - a coccolith of extremely simple construction), through the development of the genus Toweius (in which two tube cycles become well established), to the earliest form of Reticulofenestra (R. dictyoda). Since Romein's (1979) study, however, there have been emendations to the ranges of a number of Towelus species (e.g. T. eminens, T. tovae) and the recognition of some new forms, thus the early part of the lineage requires modification.

**4.4.5.2 Prinsius development :**

The transition of P. petalosus to P.dimorphosus was well documented by Romein (1979, p.71), the gradual reduction in the 'crown' of elements giving rise to a simply constructed coccolith, elliptical in outline with one or two rows of elements in the tube cycle. The reduction of the crown of elements in P. petalosus may also have given rise to P. africanus and P. tenuiculus in the Early Danian with the development of a single row of elements in the tube cycle and a circular outline. The lineage from P. dimorphosus through P. martinii to P. bisulcus can be clearly traced in the Early Palaeocene of the North Sea Basin via more regular arrangement and greater number of shield and tube cycle elements. It is clear from the ultrastructure that the Palaeocene development of the family Noelaerhabdaceae does not involve any relatively 'complex' (in terms of structure) lower Danian Biscutum forms such as B. romeinii , but may include 'simpler' Biscutum species with a similar rim construction to P.petalosus and P. africanus, or perhaps Prediscosphaera-like coccoliths.

**4.4.5.3 Toweius development :**

P.bisulcus gave rise to T. pertusus in the late Early Palaeocene which then, by rapid development of the inner tube cycle, gave rise to T. eminens, T. tovae and T. selandianus. Romein (1979, p.73) considered T. pertusus to be the ancestor of all subsequent species, but the number and diversity of reticulofenestrid species which develop in the first few million years of their existence may indicate polyphyletic origins (see Figs.43 and 44).

**4.4.5.4 Early Eocene development of Reticulofenestra :**

T. crassus (= T. callosus) is assumed to have developed from T. pertusus in the Late Palaeocene by contraction of the inner tube cycle elements and subsequent loss of the distally projected grill. T. crassus and T. pertusus range into the Early Eocene where they gave rise to R. dictyoda and R. martinii respectively. The development from Toweius to Reticulofenestra involved a re-alignment of the shield crystals orientation, as seen in the change from a dark to bright image under cross-polarised light, but the processes involved in this change are poorly understood. Perch-Nielsen (1985a, p.505) commented on the similarity in appearance of T. crassus and R.dictyoda in the light microscope. R. martinii is seldom referred to in the literature, but its strongly constructed central area grill closely resembles that of T. pertusus in proximal view.

The key developments in the transition from Toweius to Reticulofenestra are the loss of the outer tube cycle (fused with rim elements of the distal shield), an increase in imbrication of the rim elements and an increase in the birefringence of the rim in crossed-polarised light.

**4.4.5.5 Middle Eocene development of Reticulofenestra :**

The Middle Eocene was a time of rapid diversification for the reticulofenestrids with approximately ten new species arising within ten million years. R. dictyoda gave rise to R. hillae by an increase in overall size and central area opening, and to R. scrippsae by distal contraction of the tube cycle elements over the central area opening. The first occurrence datum of R. scrippsae is uncertain because of taxonomic confusion (see discussion of 13 in compendium).

In parallel with these developments, R. martinii gave rise to R. minuta (there is some dispute as to whether Eocene forms should be called R. insignita, see Pujos, 1987, p.250) by a reduction in size and ellipticity. R. coenura also developed at this time from R. martinii by expansion of the central area opening and reticulation of the central area grill (visible in crossed-polarised light). Subsequent diversification from R. coenura included R. foveolata by a reduction in overall size and slight thickening of the central area grill at its centre, R. callida by strengthening of the tube cycle and 'plugging' of the centre of the central area grill, and R. reticulata by evolution of a circular outline and a distinctive reticulate grill structure.

Middle Eocene diversification continued with the separation of R. umbilicus from R. hillae at an overall placolith size of 14um (Backman and Hermelin 1986) which is recognisable as forming a distinct population at 44.5 Ma. R. scissura developed from R. scrippsae at this time also, by an increase in overall placolith size although no limits have yet been set. R.daviesii a form very similar to R. callida, is seen to arise in the Middle Eocene by the addition of pores in the central area 'plug'.

**4.4.5.6 Late Eocene to Pliocene development development of Reticulofenestra :**

Ancestors for Late Eocene forms are less easy to recognise. R. oamaruensis, an enigmatic species, may have evolved from large forms of R. coenura (or R. onusta)- its range is very limited and published references are scarce. R. laevis is well documented by Roth (1970, p.850) from the Middle Oligocene of Alabama and appears to have a natural ancestor in R. reticulata. However, since their published ranges do not overlap this link is questionable. The range and geographic distribution of R. gartneri is poorly understood due to taxonomic confusion involving R. hesslandii (see Pujos, 1987) and a scarcity of published information, but it probably descended from R. hillae at the end of the Eocene and is a possible ancestor for R. pseudoumbilicus in the Middle Miocene.

The progression from R. perplexa to R. productella has been discussed previously (Backman 1980, Pujos 1987) and, depending on latitude, the former gives rise to the latter at some time between the Late Miocene and the Miocene / Pliocene boundary. The most likely ancestor of R. perplexa is R. scrippsae as it possesses the distinctive 'closed' central area. Backman (1980, p.44-45) defined the limits of size by which R. minuta (<3um) and R. minutula (>3um) should be separated. The change appears to occur at the base of the Miocene although confusion with taxonomy may move this into the Middle Miocene.

The evolutionary lineage described here divides the Noelaerhabdaceae genera Prinsius, Toweius and Reticulofenestra into five easily differentiated groups (which do not represent taxonomic divisions) : (see Figs.43 and 44).

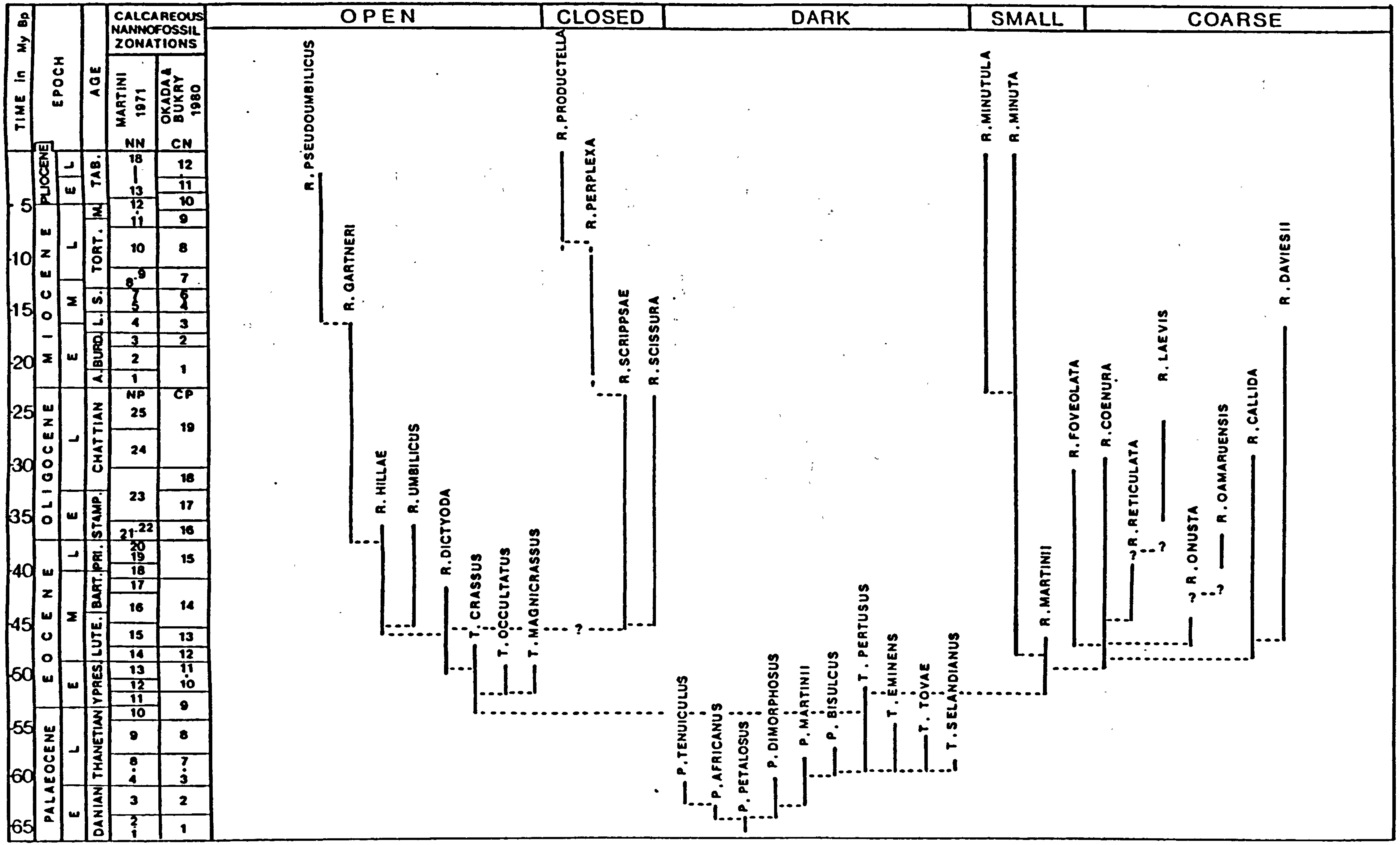
1. **OPEN** : The tube cycle produces a 'collar' around the margin of the central area, but does not contract towards the centre. The reticulate grill structures are finely constructed in the Reticulofenestra forms.

2. **CLOSED** : Reticulofenestrids in which the tube cycle is contracted over the central area so as to cover the central area grill. Members of this group have previously been assigned to the genus Dictyococcites.

3. **DARK** : : This group is restricted to small Prinsius and Toweius species in which the rim elements remain dark in cross-polarised light.

4. **SMALL** : : Confined to forms of Reticulofenestra with an overall placolith size of approximately 3um.

5. **COARSE** : : Representatives from this group consistently possess a coarse central area grill. Members of this group have previously been assigned to the genus Cribrocentrum.




Projected evolutionary development of Reticulofenestra from Prinsius and Toweius

FIG 43.

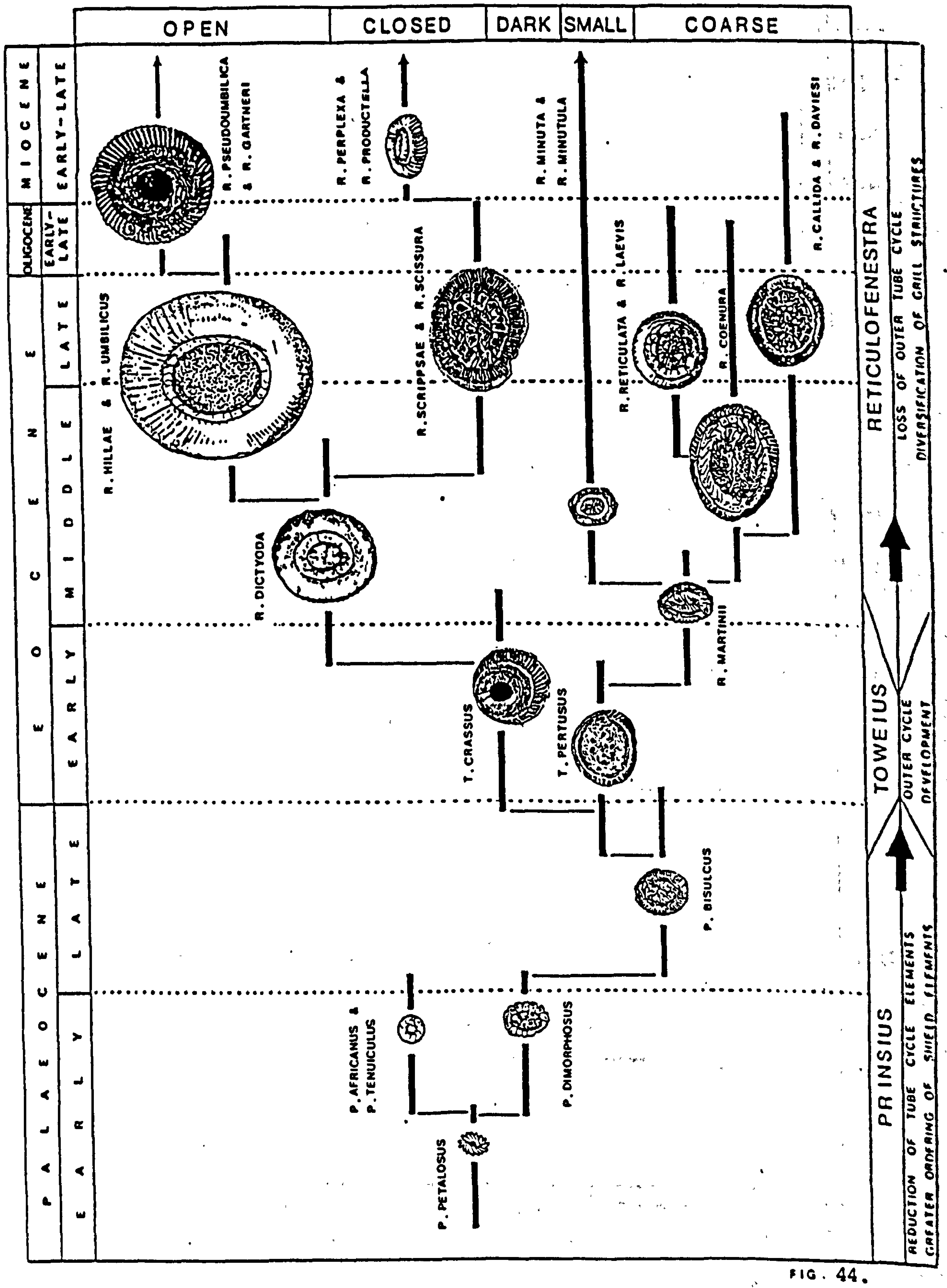



FIG. 44.

Evolution of structural morphology within the Family Noelarhabdaceae.

COMPENDIUM OF RETICULOFENESTRA SPECIES :

The following set of tables is an attempt to bring together all the commonly referenced species of Reticulofenestra in order that cross-references of similar forms may be made and is an advance upon the chart produced by Perch-Nielsen (1985b, p.87-87) in which simple, but inflexible and ambiguous structures were listed.

The information presented for each species is taken from its type description, literature sources, and the author's personal observations, then edited and the terminology standardised.

x = species considered invalid

**TABLE FORMAT**

| | |
|---|---|
| **SPECIES NAME** | **RIM STRUCTURE** |
| **AUTHOR(S)** | **Proximal and distal shield** |
| **TYPE LOCALITY** | **characteristics** |
| **AGE RANGE** | **CENTRAL AREA STRUCTURE** |
| **SHAPE AND SIZE** | **Tube cycle and central area** |
| | **grill characteristics.** |
| **REMARKS** | |

1.[x]*R. alabamensis* : Roth, 1970.
Base of Red Bluff Fmn, Lone Star Cement Qy, Alabama, U.S.A.

Distal shield has 35-40 tabular elements which imbricate strongly dextrally, sutures radial at periphery, but bend counter-clockwise at the centre. Proximal shield is slightly smaller with a similar arrangement and number of elements.

Early Oligocene (NP21-23). Small, elliptical outline. Holotype length = 3.2um, average length = 3.5-4.6um

Slits between bars of central grill along the periphery The bars join in the centre to form a raised area with irregular perforations. Central area = 50% of total coccolith area. The tube cycle consists of sinistrally imbricate tabular elements.

Remarks : Roth (1970) differentiated this species from *R. foveolata* on the basis that it had a smaller central area grill, an outer cycle of narrow slits and some small pores in the elevated central portion. However, illustrations in Haq (1971) indicate that the two species are very similar in terms of size and central area characteristics. Waghorn (1981) placed *R. clatrata* in synonymy with *R. alabamensis*, even though the former may be up to twice the size of the latter. As the holotype of *R. clatrata* is poorly preserved it is difficult to tell whether this is correct or not.

2.[x]*R. ampliumbilicus* : Theodoridis, 1984.
Sicily, Italy.

Birefringent proximal and distal shields. No data was presented for the number and arrangement of shield elements, and in the absence of electron micrographs it is not possible to comment on these.

*H. orientalis* sub-zone. (NN6)
Large, sub-circular, often circular outline.
Holotype length = 9.0um.

Large central opening, apparently lacking a central area grill. No details of the tube cycle were given and cannot be interpreted from the holotype micrographs.

Remarks : This species lacks a central area grill of any kind and is, therefore incorrectly described as a species of *Reticulofenestra*. It is more likely to belong to the genus *Cyclicargolithus*, but no formal re-combination can be attempted until electron micrographs are available.

3.[x]*R. bisecta* : (Hay, Mohler & Wade) Roth, 1970.
Nal'chik, Nal 11.

Broad distal shield of 66 elements, which are wedge-shaped and dextrally imbricate in distal view. Sutures inclined slightly clockwise. Proximal shield is smaller with the same number of elements (radial).

Late Eocene to Oligocene. (NP15-NP25)
Elliptical.
Holotype length = 8.2um, holotype width = 7.1um. Average -

Plates normally cover distal side of central area, but a central grill is proved by electron micrographs. Every third shield element contributes to the construction of the central grill. The tube cycle has "multiple" cycles of imbricate tabular elements.

length = 8.0-11.0um, average width = 7.0-9.5um.

Remarks : This form was first described in the same article as R. scissura (Hay, Mohler and Wade 1966) under the generic name Syracosphaera. It is now known that R. scissura and S. bisecta are the same species originally illustrated in different views. R. scissura was first chosen over S. bisecta and all forms subsequently described as R. bisecta must be re-named R. scissura.

4. R. callida : (Perch-Nielsen) Bybell, 1975. Orby, Denmark.

Distal shield is composed of 50-70 elements, each element forms a point at the margin. The sutures of the distal shield are sharply bent clockwise adjacent to the tube cycle. The proximal shield is slightly smaller than the distal shield, but has the same number of elements

Middle Eocene to Middle Oligocene. (NP13-NP24) Elliptical (rounded). Holotype length = 7.0um.

Diagnostic knob in centre of central area with slender radiating rods connecting it to the collar. Each tube cycle element merges into a central area grill element. (Only every second element according to Perch-Nielsen, 1971c).

Remarks : A similar species to R. daviesii, but readily distinguished in the electron microscope (less easily in the light microscope) by a complete lack of pores in the central area knob.

5. R. clatrata : Müller, 1970b Bohrung Doberg 10,0m, Germany.

Both proximal and distal shields have 30-40 elements. The poor quality of the holotype micrograph prevents comment being made on the imbrication of the elements and/or the inclination of the sutures.

Middle Oligocene (NP23-24) Elliptical. Length = 8.0-10.0um.

Large elliptical central area, wide central area grill which has 18-25 rods meeting in the middle to form an irregular grill. The rods emanate from a small inner ring of 36 elements (= tube cycle).

Remarks : May prove to be a junior synonym of R. alabamensis (see #1) and, therefore, a junior synonym of R. foveolata.

6. R. coenura : (Reinhardt) Roth, 1970. Dolgen 1/63, Germany.

50-60 elements in the distal shield. Proximal shield is smaller by the ratio 10:8, but has the same number of elements. The elements slope down to the periphery which has a serrate edge.

Early Eocene to Late Oligocene. (NP13-NP25). Elliptical. Diameter = 5.0-10.0um.

Central area is 40-50% of the total coccolith area. There are numerous small perforations in the central area grill which also has a groove along its axis.

Remarks : R. coenura is a species distinguished by its relatively large central area grill which is coarsely reticulate. Perch-Nielsen (1971c) provided excellent electron micrographs of this species and other species which it most resembles (e.g. R. foveolata) enabling the relevant distinctions to be clearly made.

7.[x]R. danica :
(Black) Roth, 1970.
Grey Marls, Grundfor,
nr Aarhus, Denmark.

40-60 slender and smoothly curved elements in each shield. Sutures only faintly visible.

Eocene to Oligocene.
(NP15-NP25).
Broadly elliptical.
Holotype distal shield = 7.2 x 6.0um.
Holotype proximal shield = 6.0 x 5.0um.
Central opening = 2.8 x 1.8um.

Central opening surrounded by a cycle of imbricate, wedge-shaped elements (tube cycle) only visible on the distal side. Central area grill bars are straight and join along the major axis of the ellipse.

Remarks : Described as having a larger central area and straighter non-anastomosing central area grill bars than R. scissura. However, only the proximal view is represented in the type description and it is considered here that R. danica should be placed in synonymy with R. scissura.

8. R. daviesii :
(Haq) Haq, 1971.
NW Germany

Numerous laminar elements in both proximal and distal shields which are slightly imbricate. Sutures inclined sharply clockwise adjacent to the tube cycle.

Eocene to Miocene.
(NP14-NN4?).
Elliptical.
Holotype length = 7.6um, holotype width = 6.4um.

10-15 pores merge to form a reticulate structure with numerous smaller pores. The central area = 40-50% of the total coccolith area. Septa form from every second or third shield element. The tube cycle consists of a number of inclined elements which may stand above the level of the distal shield. There is a perforate 'knob' in the centre of the central area grill.

Remarks : Very similar to R. callida in its general ultrastructure, but differentiated by the presence of many small pores in the central area knob.

9. R. dictyoda :
(Deflandre & Fert)
Stradner, in Stradner & Edwards, 1968.
Donzacq, France.

Wide shields with 40-60 wedge-shaped elements. The distal shield is 25-30% larger than the proximal, both shields have the same number of elements.

Early to Middle Eocene.
(NP12-NP16).
Elliptical outline.

Central area relatively small (25% of total coccolith area) contains a grill which has long holes at the margin and irregular ones in the centre. Rods are

Length = 4.0-10.0um, width = 3.9-9.0um, central grill = 1.2-4.0um.

derived from every second proximal shield element. The tube cycle is well developed with many inclined elements.

Remarks : Stradner and Edwards (1968, p.19-20) described this species in detail, placing it in the genus Reticulofenestra. However, their illustrations are of species other than R. dictyoda, hence see Haq (1971) for illustrations.

10.[x]R. falcata : (Gartner & Smith) Roth, 1970. Yazoo Fmn, Louisiana, U.S.A.

The larger distal shield has approximately 50 elements which are terminated in a rounded point. Viewed proximally the sutures of the distal shield are slightly curved, inclined clockwise and imbricate sinistrally.

Late Eocene (NP19/20). Slightly elliptical. Maximum diameter = 7.5um.

The central opening is elliptical and contains the remnants of a grill. The tube cycle is an elliptical cylinder having knob-like protrusions where it joins the proximal shield.

Remarks : The electron micrographs shown by Gartner and Smith (1967, pl.1, figs. 5,6) are inconclusive, but strongly resemble R. scissura, thus R. falcata is superfluous and is considered a junior synonym of R. scissura.

11.[x]R. floridana : (Roth & Hay) Theodoridis, 1984. JOIDES 5, Blake Plateau, 554' 10" below top.

Placolith with 40-41 dextrally imbricate elements separated by sutures having a slight clockwise inclination on the distal surface, but straight on the proximal surface. Both proximal and distal shield have the same number of elements.

Early Eocene to early Middle Miocene. (NP14- NN6) Circular to broadly elliptical. Holotype diameter = 3.6um. paratype diameter = 4.1-5.0um.

The tube cycle consists of a series of stout, uneven blocks. The central opening is approximately 33% of the total coccolith area and lacks a grill of any kind.

Remarks : Theodoridis (1984, p.85) assigned this form to the genus Reticulofenestra rather than Cyclicargolithus. However, as no central area grill of any style or geometry has ever been found it is considered to belong to the genus Cyclicargolithus.

12. R. foveolata : (Reinhardt) Roth, 1970. Bohrung Bad Doberan, 5/61.

Distal shield of 34-36 elements, the proximal shield is 10% smaller, but has the same number of elements. Perch-Nielsen (1971c) quotes 50-70 elements in the shields.

| | |
|---|---|
| Middle Eocene to Late Oligocene (NP14-NP23). Small, elliptical. Length = 2.5-6.0um, width = 2.0-2.3um. | Central area is 60% of the total diameter. The septa enclose long pores. An outer ring of slit-like perforations surrounds an area pierced by 18-26 small, circular holes. Tube cycle of flat rectangular crystals. |

Remarks : Roth (1970, p.848) differentiated this species from R. insignita by its narrower rim and fewer elements and by its more elongate pores in a relatively larger central area grill. Comparison of the type figures of R. foveolata, R. insignita and R. alabamensis suggests strong similarity between the characteristics listed above (differences attributable to preservational effects ?) and it is suggested that the two latter species be placed, therefore, in synonymy with the former as it was the first to be described.

| | |
|---|---|
| 13. R. gabrielae : Roth, 1970. 13' above base of Red Bluff Fmn, Lone Star Cement Qy, Alabama, U.S.A. | 18-22 wedge-shaped, dextrally imbricate elements in the distal shield. Elements are separated by radial suture lines. Detail of the proximal shield is not known. |
| Oligocene (NP21-NP25). Very small. Length = 1.8um. | Relatively large central area grill with approximately 50 pores arranged regularly more or less parallel to the ellipse. No wedges present around central area grill (= no tube cycle present). |

Remarks : The fact that the tube cycle is absent is clearly a preservational trait and there is no valid reason to erect a new genus. R. gabrielae is similar to R. foveolata, but has fewer elements, more circular perforations, and is much smaller.

| | |
|---|---|
| 14. R. gartneri : Roth & Hay, 1967. JOIDES 5, Blake Plateau, 554' 10" below top. | Distal shield has 150 fine, thin elements which are inclined counter-clockwise in distal view. The proximal shield is slightly smaller than the distal shield, with the same number of elements. |
| Early Oligocene to Early Miocene. (NP21-NN4). Broadly elliptical, smooth outline. Length = 5.8um. | Central grill perforated by approximately 120 small holes which are circular to oblong in shape. There are no marginal slits. The tube cycle consists of a ring of imbricate elements. |

Remarks : R. gartneri lacks the slits around the margin of the central area as seen in R. caucasica and R. insignita according to Roth and Hay (1967) and has a wider outline and more pores in the relatively smaller central area. The electron micrograph figured as the holotype resembles R. coenura, but has a more finely perforate central area grill. Pujos (1987) noted that this form is latitudinally restricted and, presumably for this reason, rarely quoted in the literature. It is considered to be a possible ancestor of R. pseudoumbilicus and may be synonymous with R. tenuistriata (Varol, pers. com.).

15. [x]R. gelida : (Geitzenauer) Backman, 1978. Pacific sub-antarctic deep sea core, Eltanin 25-11, 520-640cm.

Numerous (68-74) slightly imbricated elements in the distal shield. Between crossed-nicols the entire shield is strongly birefringent. Extinction cross clearly visible to the edge of the shields.

Late Pliocene. (NN15-NN18). Oval-shaped. Size = 6.0-12.0um.

Central area usually filled with a wall of irregularly shaped calcite crystals (= tube cycle). Central opening circular to slit-like. No bridge in central area.

Remarks : Clearly differentiated from C. pelagicus as outlined by Geitzenauer (1972), but not so definitely from R. pseudoumbilicus as discussed by Backman (1980). Only in high latitudes and in placoliths exceeding 140um² in area can a difference be detected, and only then in the size of the central opening. Pujos (1987) considered R. gelida to be a sub-species of R. pseudoumbilicus. However, this is unnecessary splitting and it is recommended herein that R. gelida be considered a junior synonym of R. pseudoumbilicus.

16. [x]R. hampdenensis : Edwards, 1973. Hampden Fmn, above basal Greensand, Hampden Beach, New Zealand.

28-55 strongly sinistrally imbricate elements in both shields. Proximal shield has parallel sutures and a serrate margin, whereas the distal shield is made up of narrow wedge-shaped elements with counter-clockwise inclined sutures.

Middle Eocene. (NP14-NP18). Oval to sub-circular. Holotype length = 3.7um.

"Marginally spoked and centrally hubbed" central area. Fenestrate part of the grill results from 50-90% of the proximal shield elements attenuating into the central opening. The tube cycle is a wall of distally expanding laths with parallel sutures.

Remarks : Edwards (1973) examined thousands of light and scanning electron micrographs of forms which he assigned to R. hampdenensis, being unable to find natural criteria to split them. He demonstrated how R. hampdenensis could be distinguished from R. dictyoda and R. placomorpha, but the holotype is thought to be a specimen of R. coenura , making R. hampdenensis a junior synonym of R. coenura. Detailed examination of topotype material revealed an assemblage containing R. coenura, R. foveolata, R. callida and R. daviesii where Edwards (op. cit.) had only listed R. hampdenensis.

17. [x]R. haqii : Backman, 1978. Vera Basin, sample 11.

Distal and proximal shields equal in size and built up of 40-50 elements each. The narrow crystal elements are not discernible in the light microscope.

Early Miocene to Early Pliocene. (NN2-NN13). Small, elliptical.

Tube cycle may distally consist of coarse crystallites, but is thin in many specimens. Small central opening, in which a grill may be seen on the proximal side.

Length = 3.0-5.0um,
central opening =
1.0-1.5um.

Remarks : Resembles R. pseudoumbilicus in possessing a central opening surrounded by a tube cycle and in having rather similar crossed nicols images, but it is distinguished by its consistently smaller size. Backman (1980) separated R. haqii from R. minuta and R. minutula on the basis of very small differences in the overall diameter and central opening diameter. Pujos (1987) recognised R. haqii and R. minutula as ecotypes of the same species. As their spatial and temporal distributions are closely similar there is no reason to separate R. haqii from R. minutula, thus the former is considered a junior synonym of the latter.

18.[x] R. hesslandii : (Haq) Roth, 1970. Tabqa, NW Syria.

39 elements in proximal shield, 40-45 elements in the distal shield. Roth (1970) quoted 60 elements in the proximal shield. Sutures of distal shield are inclined sharply clockwise adjacent to the tube cycle.

Late Eocene to Oligocene (NP19-NP25). Very variable in size, shape and number of shield elements. Usually circular to sub-circular. Diameter = 2.8-9.1um, central opening = 0.5um.

Coarse central grill. Central opening is approximately 20% of the total size of the coccolith. The grill is composed of irregular, twisting bars. The tube cycle consists of 6-8 large, irregular elements.

Remarks : Distinguished from C. floridanus by the presence of a coarse grill in the central area. It is obvious that the taxonomy of this species is in considerable doubt as Backman (1987) considered it to be synonymous with R. scrippsae, whilst Pujos (1987) separated them on the basis of overall size; R. scrippsae = 7.6-10.0um, R. hesslandii = 2.8-6.3um, and suggested that R. hesslandii evolved from R. scrippsae.

19. R. hillae : Bukry & Percival 1971. Shubuta member, Yazoo Clay, Chickasaway R., Mississippi, U.S.A.

Wide shields very similar to those of R. umbilicus. The distal shield elements are slightly imbricated, whilst those in the slightly smaller proximal shield are more or less radial. (Same number in each shield).

Middle Eocene to Late Oligocene. (NP15-NP22). Large elliptical outline, wide elliptical tube cycle and small central area.

Thick, wide, elliptical tube cycle. Small central opening, approximately 33% of the total length of the coccolith. Fine central area grill visible in the electron microscope.

Remarks : R. hillae is differentiated from Cyclicargolithus abisectus by its elliptical shape and larger central opening. The distinction from R. umbilicus, however, based on a wider tube cycle and correspondingly smaller central opening is less certain. Backman and Hermelin (1986) conducted a thorough morphometric study on these two species and found a complete gradation in terms of overall size and central opening size. They concluded that R. hillae may be an ecophenotype of R. umbilicus, but for biostratigraphic purposes a diameter of <14um should be used to recognise R. hillae, and >14um for R. umbilicus.

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| 20. R. inclinata : Roth, 1970. JOIDES 5, Blake Plateau, 484' below top. | Chevron-shaped elements in distal shield; 34-40 tabular and dextrally imbricate. Suture lines inclined counter-clockwise in outer half of shield, then turn sharply in inner half of shield. Proximal shield is slightly smaller than the distal shield, but has the same number of elements. |
| Oligocene (NP21-NP25). Narrow elliptical outline. Length = 3.8um. | Central grill has nearly straight bars with long intermediate slits. Central area occupies approximately 66% of the total length of the coccolith. No apparent tube cycle. |

Remarks : The identity of this species is in some doubt because of the poor preservation of the holotype (tube cycle absent). The lack of published references since its original description is testimony to its somewhat ambiguous position.

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| 21. x R. insignita : Roth & Hay, 1967. JOIDES 5, Blake Plateau, 410' below top. | Large number of fine elements in the distal shield. Proximal shield is constructed of approximately 50 elements separated by sutures with slight counter-clockwise inclination in proximal view. |
| Oligocene (NP21-NP25). Narrowly elliptical. Length = 3.7um. | Slits around the margin of the central area. 36 round perforations in the central grill which takes up approximately 50% of the total area of the coccolith. The tube cycle consists of narrow rectangular elements. |

Remarks : R. insignita is distinguished from R. gartneri by having a more narrowly elliptical outline, relatively larger central area, and by having a ring of slits around the margin of the central area. It is difficult to imagine how these two species can be confused when Pujos (1987) compares R. insignita to R. minuta, and R. gartneri to R. pseudoumbilicus - a potential size difference of 10.0um! R. insignita closely resembles R. foveolata and may prove to be a junior synonym of it. Pujos (op. cit.) also discussed the possibility that R. insignita may have been ancestral to R. minuta.

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| 22. R. laevis : Roth & Hay, 1967. JOIDES 5, Blake Plateau, 337' 11" below top. | Distal shield sub-circular and smooth, composed of approximately 140 poorly defined elements. Proximal shield is 85% of the size of the distal shield and also has a large number of elements. Margin finely serrate and sutures inclined counter-clockwise. |

Middle Oligocene. (NP23/24). Sub-circular outline. Holotype length = 6.4um.

Small round central opening spanned by a grill of approximately 30-40 small round perforations. Tube cycle elements show strong imbrication.

Remarks : The distal shield has an outer cycle of 60-80 elements, not 140 as stated in the type description. It is also described as the most nearly circular species of Reticulofenestra, but this does not take account of R. reticulata which was described in the same year as R. laevis and which is almost perfectly circular. It is possible that the close similarity in morphologies of these two species represents an evolutionary link. However, there is a gap between their published ranges, thus this link remains tentative.

23.[x] R. lockeri : Muller, 1970b Farve I, 149.0-150.0m.

Distal shield has 50-60 fine, radially arranged elements. The proximal shield has a similar number of elements as the distal shield, but is slightly smaller.

Middle Oligocene. (NP23/24). Mildly elliptical outline. Diameter = 8.0-12.0um.

Large elliptical central area grill which has a number of more or less regular pores. In the tube cycle there are 20-22 almost rectangular elements.

Remarks : Waghorn (1981, p.53) considered this form to be a junior synonym of R. coenura. The central area of the holotype as illustrated by Muller (1970b) is preservationally altered, thus difficult to classify. Overall size, shape and shield structure appear consistent with placement in R. coenura.

24. R. martinii : (Hay & Towe) nov. comb. Tuilerie de Donzacq, Landes, France.

Distal and proximal shields with the same number of elements, some of which contribute to the central area grill. Proximal shield slightly smaller than the distal shield with approximately the same number of elements.

Eocene (NP11-NP14). Shields narrow, Elliptical outline. Holotype length = 2.2um. Length = 1.9-2.9um, width = 1.3-2.4um.

Tube cycle has 25 wedge-shaped, dextrally imbricate elements, the sutures of which have clockwise inclination. Each element of the proximal shield contributes to the central area grill.

Remarks : A little known species characterised by a lack of reticulation in the central area grill, which consists of a relatively small number of coarse rods meeting along the long axis of the coccolith.

25. R. minuta : Roth, 1970. 10' above base of

16-22 elements in distal shield which are dextrally imbricate and wedge-shaped. The sutures are inclined in a clockwise direction. The proximal shield is almost

Red Bluff Fmn, Lone Star Cement Qy, Alabama, U.S.A.

the same size as the distal and consists of 16-26 wedge-shaped elements with counter-clockwise inclined sutures.

Middle Oligocene to Pliocene (NP12-NN18). Very small, elliptical. Length = 2.3-4.0um.

Ring of elements surround the central opening. (= tube cycle). 10-15 pores in central grill separated by coarse bars. Central opening occupies approximately 33% of the total area of the coccolith.

Remarks : R. foveolata has a larger central area and more numerous pores than R. minuta which appears to lack a central area grill under crossed nicols. Backman (1980, p. 44-45) separated R. minuta and R. minutula on the basis of the former being <3.0um in size and the latter being >3.0um in size. Pujos (1987) refers Palaeogene examples of R. minuta to R. insignita (see #21).

26. R. minutula : (Gartner) Haq & Berggren, 1978. 200cm depth, core 64-A-9-5E, Sigsbee knolls, Gulf of Mexico.

Shields have approximately 45 imbricate elements, with sub-radial sutures. Each element of the proximal shield is curved in the proximal direction.

Early Miocene to Pliocene. (NN2-NN18). Small, elliptical. Length = 3.5um.

Tube cycle protrudes distally and is continuous with the proximal shield. Central area is open distally, but contains a simple grill proximally.

Remarks : Differs from E. huxleyi in not having a gap between adjacent elements of the shield. Gartner (1967a) stated that its small size separated it from associated species in the light microscope, but this fails to take into account R. minuta and R. haqii. Backman (1980) and Pujos (1987) have discussed the taxonomy of these three species in detail and with conflicting conclusions. It is probably reasonable to include R. haqii as a junior synonym of R. minutula and to separate R. minuta on the criteria suggested by Backman (1980) (see #25).

27. R. oamaruensis : (Deflandre & Fert) Stradner in Stradner & Edwards, 1968. Diatomite, William's Bluff, Oamaru, New Zealand.

Distally convex, 80-100 wedge-shaped elements. Proximal shield very slightly smaller than the distal shield, with a similar number of elements.

Late Eocene to Middle Oligocene. (NP20-NP22). Elliptical outline. Length = up to 18.0um, width = up to 15.0um.

A wide reticulate "membrane" with 9-13 concentric rows of oblique pores covers the central opening. The diameter of the "membrane" is greater than 50% of the total diameter of the coccolith. The tube cycle is unique in that the narrow, imbricate elements project high above the level of the distal shield.

Remarks : R. oamaruensis is differentiated from R. umbilicus by the different proportions of the diameters of central area grill and shield, and by the number shape and size of pores. R. oamaruensis has no marginal fenestration, only reticulation in a strict geometrical pattern. Investigation of topotype material has revealed that this species has a distally projected tube cycle unlike that in many other species of Reticulofenestra.

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| 28. R. onusta : (Perch-Nielsen) Wise, 1983. Orby, Denmark. | Distal shield has 60-70 almost radial elements, as does the smaller proximal shield. |
| Eocene (NP14-NP16). Large, elliptical. Length = 8.0-11.0um. | Relatively wide and relatively flat central area of two layers of net forming elements. Central area grill slightly raised, a suture runs along the long axis of the grill. A groove separates the central area from the rim elements. The tube is sometimes absent, but usually consists of a low ring of imbricate, rectangular laths. |

Remarks : Differs from R. daviesii and R. callida in the structure of the central area. Lacks a 'lath covering in line with the central area' (a tube cycle) according to Wise (1983). However, micrographs shown by Wise (1983) and Perch-Nielsen (1971c) clearly illustrate the presence of a tube cycle. It is the author's experience that the tube cycle is often absent in this species, but it certainly exists. The stratigraphic position and complex structure of this species might be indications of it being an ancestor of R. oamaruensis.

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| 29. $^{x}$R. ornata : Müller, 1970b Bohrung Fussung I, 521.8m, Bandermergel. | Proximal shield has 60-70 fine elements, almost radially disposed. The characteristics of the distal shield were not described and are not known from other sources. |
| Oligocene (NP23). Slightly elliptical. Length = 6.0-7.0um. (May be up to 10.0um). | Grill on proximal side of central area and a fine "net" on the distal side with numerous pores. The "net" rods are arranged like the hands of a clock. The central area grill covers approximately 50% of the total coccolith area. |

Remarks : Waghorn (1981, p.53) considered this species to be a junior synonym of R. coenura, however, it shows more affinity to R. scissura. The rods of calcite in the central area probably result from preservational effects.

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| 30. $^{x}$R. pectinata : Roth, 1970. 13' above base of Red Bluff Fmn, Lone Star Cement Qy, Alabama, U.S.A. | Distal shield constructed of 50-60 wedge-shaped, dextrally imbricate elements with clockwise inclined sutures. the margin is serrate. The proximal shield appears to be smaller than the distal, with a similar arrangement of elements. |
| Oligocene (NP21-NP23). Small. | Tube cycle has 40-50 wedge-shaped sinistrally imbricate elements. Wide, coarse grill with long slits between |

Length = 3.5um. bars which are continuous with every second element. Central opening covers 60% of the total coccolith area.

Remarks : Roth (1970, p.851) distinguished this species from R. alabamensis on the basis of it having a relatively larger central opening and more numerous elements in the shield. Examination of the micrographs of both holotypes reveals that R. alabamensis has a central opening which occupies approximately 60% of the total length of the coccolith, as does R. pectinata, and both species have approximately 45 elements in the shield. Hence, these two forms are synonymous and both are junior synonyms of R. foveolata.

31.[x]R. pelycomorpha : (Reinhardt) Perch-Nielsen, 1985a Bohrung Dolgen 1/63. Distal shield has 80-90 slightly imbricate elements. The proximal shield is 25% smaller, with a similar number of radially arranged elements.

Eocene (NP16?) Elliptical. Length to width ratio = 10 : 8. Length = 11.0-14.0um. Central area is 33-50% of the total length of the coccolith and contains a fine grill. The tube cycle consists of a ring of imbricate elements around the central area grill.

Remarks : This form is considered separate from R. placomorpha by Reinhardt (1966) on the basis that the percentage of the total length taken up by the central area is different. It is clear, however, that these two species are synonymous.

32. R. perplexa : (Burns) Wise, 1983. DSDP Site 125-16-6, depth 25-26cm. Medium-sized, finely striate distal shield, prominent in cross-polarised light. Composed of many thin inclined elements. The proximal shield is smaller than the distal and the two are not closely adpressed.

Upper Early to lower Late Miocene. (NN3-NN9?). Medium-sized, elliptical. Length = 5.0-6.0um. Medium-sized central area, bright between crossed-nicols. No central perforation, but a "tortuous" line can be seen in the centre of the central area. The central area on the distal surface is composed of many small elements arranged in a counter-clockwise direction emanating from the distal part of the tube cycle.

Remarks : Distinguished by its prominent centre, lack of central perforation and particularly by the tortuous line in the central area. Backman (in van Heck 1981, p.40) pointed out that D. antarcticus Haq is a junior synonym of this species. This escaped most author's attention according to Wise (1983) because of scaling errors in Burns' (1975) original description. All of the magnifications are overstated by a factor of approximately 2.5, hence the holotype of 'D. perplexa' should measure 5.0-6.0um in length, not 18.0-20.0um as originally quoted.

33. R. placomorpha : (Kamptner) Stradner, Distal shield has 60-100 imbricate, wedge-shaped elements. Proximal shield is smaller, but has the same

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| in Stradner & Edwards, 1968. Inner Alps, Weiner Basin. | number of elements. |
| Middle Eocene to Early Oligocene. (NP16-NP22). Elliptical. Length = up to 15.0um, width = up to 12.0um. | Large central opening spanned by a grill with elongate fenestration marginally and reticulate fenestration centrally. Imbricate elements of the tube cycle may extend towards the centre and close the central area distally. |

Remarks : When first introduced by Kamptner (1948) Tremalithus placomorphus was invalid as it had only been conditionally erected. Deflandre (1952) is quoted as having validated the name, but there may be some dispute in this under Art.32.2 of the I.C.B.N. However, the specific name was validated by Kamptner (1956) as Coccolithus placomorphus by reference to previously published descriptions and figures. This species is often put in synonymy with R. umbilicus, and it is the author's opinion that detailed morphometric analysis is necessary to establish whether these are the same species or not.

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| 34. R. productella : (Bukry) nov. comb. Pacific Ocean. | The larger distal shield is composed of approximately 28-40 wedge-shaped, slightly imbricate elements. The sutures between elements are slightly inclined. The periphery of the shield is serrate. The proximal shield which also has a serrate edge is concave and contains the same number of elements as the distal shield. |
| Middle Miocene to Recent(NN6?-NN21). Small, elliptical. Length = 3.5-4.5um. | Central area closed distally by a covering of irregular calcite laths emanating from the tube cycle (details of which are obscured). A slit divides the central area along its long axis. The extinction figure in the central area has a distinctive swastika shape. |

Remarks : This species is distinguished from R. perplexa on the basis of overall size. The name R. producta has been widely used for this species in the past, but is not valid. In 1963 Kamptner erected the taxa Ellipsoplacolithus productus which is invalid due to the fact that it was conditionally erected (Art. 34.1) Sachs and Skinner (1973) combined this species name into the genus Coccolithus, claiming that it would be validated by doing so (Art. 34). However, this is not the case, and it was not until Bukry (1975) erected the name Crenalithus productellus with reference to his figure of Gephyrocapsa producta in Bukry 1971b that the form became legitimately named.

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| 35. R. pseudoumbilicus : (Gartner) Gartner, 1969a 250cm depth, core 64-A-9-5E, Sigsbee knolls, Gulf of Mexico. | About 70 radial elements in both proximal and distal shields. Very similar light microscope image to that of R. umbilicus and R. hillae. |

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| Middle Miocene to Pliocene (NN5-NN18). Relatively large elliptical outline. Holotype length = 8.0um. | Central area size varies and contains a reticulate grill. Tube cycle may have large coarse elements. The central opening generally takes up less than 50% of the total coccolith area. |

Remarks : Resembles R. umbilicus and R. dictyoda somewhat, from which it has a large temporal separation. More relevant is its similarity to R. gartneri from which it may well have evolved. The first occurrence datum of R. pseudoumbilicus corresponds to the last occurrence datum of R. gartneri. Varol (pers. com.) used the name R. tenuistriata for forms between 5.0-7.0um in length, and R. pseudoumbilicus for forms >7.0um.

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| 36. R. reticulata : (Gartner & Smith) Roth & Thierstein, 1972. Yazoo Fmn, Louisiana, U.S.A. | 50-70 imbricate elements in the distal shield with radial sutures which incline and curve slightly clockwise. Sutures of proximal shield are irregular near the centre but become straight near the periphery, and may imbricate slightly dextrally and incline slightly counter-clockwise. |
| Middle to Late Eocene (NP17-NP20). Circular. Maximum diameter = 6.0-9.0um. | Central opening spanned by a grill and surrounded by a tube cycle of strongly imbricate elements as seen in distal view. Grill is slightly arched. Unique extinction cross in centre under cross-polarised light. |

Remarks : Gartner and Smith (1967) differentiated R. reticulata and R. dictyoda on the basis of its greater number of elements per shield. However, the distinction is much clearer than that, in so far as the circular outline of R. reticulata and its prominent central area grill with obvious extinction cross under cross-polarised light are specific characteristics which make it one of the most readily recognisable species of Reticulofenestra.

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| 37.[x]R. rotaria : Theodoridis, 1984. DSDP 29, Indian Ocean. | Birefringent distal and proximal shields. No electron micrographs of this species have been published, thus no comment on the number and arrangement of elements in the shields can be made. |
| R. rotaria Zone, Late Miocene (NN11). Small, circular. Maximum diameter = 5.0-7.0um. | Relatively large, circular central opening. No central area grill is present and no tube cycle has been described. If a tube cycle can be proven it is likely that this species will belong to the genus Cyclicargolithus. |

Remarks : R. rotaria cannot be a species of Reticulofenestra as no central area grill has been illustrated or described. It is probably better allocated to Cyclicargolithus.

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| 38.[x]R. samodurovii : (Hay, Mohler & Wade) | Distal shield has 54-55 imbricate elements. Sutures have slight clockwise inclination in distal view. |

Roth, 1970.
Nal'chik, Nal 11.

Late Eocene to Late Oligocene. (NP19/20-NP25). Broadly elliptical. Length = 5.0-12.0um, width = 4.0-11.0um.

Proximal shield not as wide as distal shield, but has a similar number of elements.

Central opening is 33% of total length of the coccolith Tube cycle has 54-55 tall lath-like elements having sinistral imbrication in distal view. Finely constructed central area grill.

Remarks : Differentiated from R. umbilicus by being smaller and having a relatively smaller central opening. Considered by many authors to be synonymous with R. umbilicus, though in view of Backman and Hermelin's (1986) morphometric study it may better be considered a junior synonym of R. hillae.

39. R. scissura : Hay, Mohler & Wade, 1966.
Nal'chik, Nal 11.

Middle Eocene to Late Oligocene. (NP16-NP25). Elliptical outline. Holotype length = 8.0um, holotype width = 7.4um, length = 6.4-10.0um, width = 5.4-9.0um.

40-66 wedge-shaped elements with strong sinistral imbrication in proximal view. Proximal shield is smaller than the distal, but has the same number of elements and straight sutures.

Central opening occupies approximately 25% of the total coccolith diameter and is spanned by 8-11 anastomosing laths which produce elongate fenestration. The tube consists of a ring of flat, imbricate crystals which may project over the central opening to obscure the proximally positioned grill.

Remarks : R. scissura and R. bisecta are considered synonymous despite the assertion of Hay, Mohler and Wade (1966) that R. scissura is slightly smaller and has a wider central area grill. Many of the specimens figured by Stradner and Edwards (1968) as R. dictyoda are herein considered to be R. scissura.

40. R. scrippsae : (Bukry & Percival) Roth, 1973.
Red Bluff Clay, Chickasaway R., Shubuta, Mississippi, U.S.A.

Middle Eocene to Late Oligocene. (NP16-NP25) Small, elliptical. Diameter = 6.0-12.0um.

Similar construction to R. scissura. The distal and proximal shields have numerous wedge-shaped elements. The proximal shield is smaller, but has the same number of elements with straight sutures.

Solid central area composed of radial calcite laths (= covering over central area grill), extending from the imbricate, rectangular elements of the tube cycle.

Remarks : In the type description of R. scrippsae it is differentiated from R. scissura on the basis of its smaller size, more elliptical outline and continuous, sharply bent extinction lines. Backman (1987) considered this species to be a junior synonym of R. hesslandii, but a consideration of overall size (see #18) determines whether these forms are split or not. It appears that R. hesslandii is smaller than R. scrippsae which is smaller than R. scissura, though no formal parameters have yet been established. Such a relationship of size ranges may represent an evolutionary scheme or just taxonomic oversplitting.

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| 41.[x] R. tokodensis : Baldi-Beke, 1982. Borehole Many 181, 338m. | 80-100 elements in the distal shield. Straight sutures and straight extinction cross. Proximal shield 15-20% smaller than distal shield, with the same number of elements. |
| Middle Eocene. (NP14-NP18). Large, broadly elliptical. Length = 8.0-13.0um. | Large, empty central area under cross-polarised light. Thick tube cycle. Central opening = 30-60% of the total coccolith area. |

Remarks : Similar to R. ornata according to Baldi-Beke (1982, p.300), but has a straight extinction cross, wider central area and a thicker tube cycle. The micrographs of the holotype and isotypes figured by Baldi-Beke (1982 , 1984) are of very poor quality and illustrate specimens obviously greatly altered by preservational effects. The true assignation of this form (similar to R. hillae, R. umbilicus) is in doubt until better preserved specimens can be adequately figured.

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| 42. R. umbilicus : (Levin) Martini & Ritzkowski, 1968. Sample 27A, 42.6-109.5 WUMC 000023, Yazoo Fmn, Mississippi, U.S.A. | Large proximal and distal shields, very thin sutures visible. The peripheral margin is slightly serrate. Each shield contains many elements, radially arranged. |
| Middle Eocene to Early Oligocene. (NP16-NP22). Large circular to slightly elliptical. Length = >14.0um (Backman and Hermelin 1986). | Robust tube cycle of many imbricate laths surrounds a large central opening (up to 70% of total coccolith area). The central area grill is a very fine meshwork of thin laths. Each proximal shield element contributes to the construction of the central area grill. |

Remarks : An extensive synonymy list for this species is given by Waghorn (1981 p.71-73). It is usually a very distinctive species, though morphometric studies such as that by Backman and Hermelin (1986) have proved necessary to distinguish it from similar forms.

4.4.7 SUMMARY LIST OF RETICULOFENESTRA SPECIES :

Species are listed alphabetically. Senior synonyms are followed by a list of junior synonyms and possible junior synonyms; whilst junior synonyms are followed by the reference number of their senior synonym.

* = a species not quoted in the compendium due to infrequency of use, but with connections to a more well known species.

1. R. alabamensis Roth 1970 = see #13.
2. R. ampliumbilicus Theodoridis 1984 = Cyclicargolithus ampliumbilicus ?
3. R. bisecta (Hay, Mohler and Wade 1966) Roth 1970 = see # 41.
4. R. callida (Perch-Nielsen 1971c) Bybell 1975.
5. *R. caucasica Hay, Mohler and Wade 1966 = see #45.
6. R. clatrata Müller 1970b = see #13.
7. R. coenura (Reinhardt 1966) Roth 1970 = R. hampdenensis, R. lockeri ?
8. R. danica (Black 1967) Roth 1970 = see #41.
9. R. daviesii (Haq 1968) Haq 1971.
10. R. dictyoda (Deflandre and Fert 1954) Stradner in Stradner and Edwards 1968.
11. R. falcata (Gartner and Smith 1967) Roth 1970 = see #41.
12. R. floridana (Roth and Hay 1967) Theodoridis 1984 = Cyclicargolithus floridanus (Roth and Hay, 1967).13.
13. R. foveolata (Reinhardt 1966) Roth 1970 = R. alabamensis, R. clatrata?, R. insignita?, R. pectinata.
14. R. gabrielae Roth 1970.
15. R. gartneri Roth and Hay 1967 = R. tenuistriata ?
16. R. gelida (Geitzenauer 1972) Backman 1978 = see #37.
17. R. hampdenensis Edwards 1973 = see #7.
18. R. haqii Backman 1978 = see #27.
19. R. hesslandii (Haq 1966) Roth 1970 = see #42.
20. R. hillae Bukry and Percival 1971 = R. samodurovii ?, R. tokodensis.
21. R. inclinata Roth 1970 = legitimacy in doubt, but no obvious synonym.
22. R. insignita Roth and Hay 1967 = see #13.
23. R. laevis Roth and Hay 1967.
24. R. lockeri Müller 1970b = see #7.
25. R. martinii (Hay and Towe 1962) nov comb.
26. R. minuta Roth 1970.
27. R. minutula (Gartner 1971) Haq and Berggren 1978 = R. haqii.
28. R. oamaruensis (Deflandre and Fert 1954) Stradner in Stradner and Edwards 1968.
29. R. onusta (Perch-Nielsen 1971c) Wise 1973.
30. R. ornata Müller 1970b = see #41.
31. R. pectinata Roth 1970 = see #13.
32. R. pelycomorpha (Reinhardt 1966) Perch-Nielsen 1985a = see #34.
33. R. perplexa (Burns 1975) Wise 1983 = Dictyococcites antarcticus Haq 1976.
34. R. placomorpha (Kamptner 1948) Stradner in Stradner and Edwards 1968 = R. pelycomorpha.
35. *R. prebisecta Aubry 1983 = see #42.
36. R. productella (Bukry 1975) nov. comb.
37. R. pseudoumbilicus (Gartner 1967a) Gartner 1969a = R. gelida, R.

tenuistriata.
38. R. reticulata (Gartner and Smith 1967) Roth and Thierstein 1972.
39. R. rotaria Theodoridis 1984 = Cyclicargolithus rotaria?
40. R. samodurovii (Hay, Mohler and Wade 1966) Roth 1970 = see #20.
41. R. scissura Hay, Mohler and Wade 1966 = R. bisecta, R. danica, R. falcata, R. ornata ?
42. R. scrippsae (Bukry and Percival 1971) Roth 1970 = R. hesslandii, R. prebisecta.
43. *R. tenuistriata (Kamptner) Martini 1979 = see #15 and 37.
44. R. tokodensis Báldi-Beke 1982 = see#20 and 45.
45. R. umbilicus (Levin 1962) Martini and Ritzkowski, 1968 = R. caucasica (Hay, Mohler and Wade 1966), R. samodurovii ?, R. tokodensis.

## PLATE i : RETICULOFENESTRA

1,2,3 & 4. Reticulofenestra umbilicus (Levin) Martini and Ritzkowski : Fig.1 UCL-2553-31 proximal view of a broken specimen showing structural relationship between the proximal shield and the tube cycle, X5,000; Fig.2 UCL-2423-26 central area grill detail (distal view) showing the tube cycle to grill rod structural relationship, X10,000; Fig.3 UCL-2423-06 oblique side view, X7,500; Fig.4 UCL-2553-33 distal view of a specimen which lacks a tube cycle, X5,000. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene.

5,8 & 11. Reticulofenestra scissura Hay, Mohler and Wade : Fig.5 UCL-2216-07 proximal view of central area grill structure and proximal shield elements, X10,000; Fig.8 UCL-2216-03 proximal view, X5,000; Fig.11 UCL-2216-05 distal view of an overgrown specimen, X5,000. Shell/Esso North Sea well number 29/10-1, depth 7122'. Early Oligocene.

6. Reticulofenestra daviesii (Haq) Haq : UCL-2335-12 distal view of a slightly overgrown central area. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene. X7,500.

7 & 13. Reticulofenestra hillae Bukry and Percival : Fig.7 UCL-2423-19 oblique distal view of a broken specimen; Fig.13 UCL-2553-32 distal view. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X5,000.

9. Reticulofenestra callida (Perch-Nielsen) Bybell : UCL-2335-22 distal view. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene. X5,000.

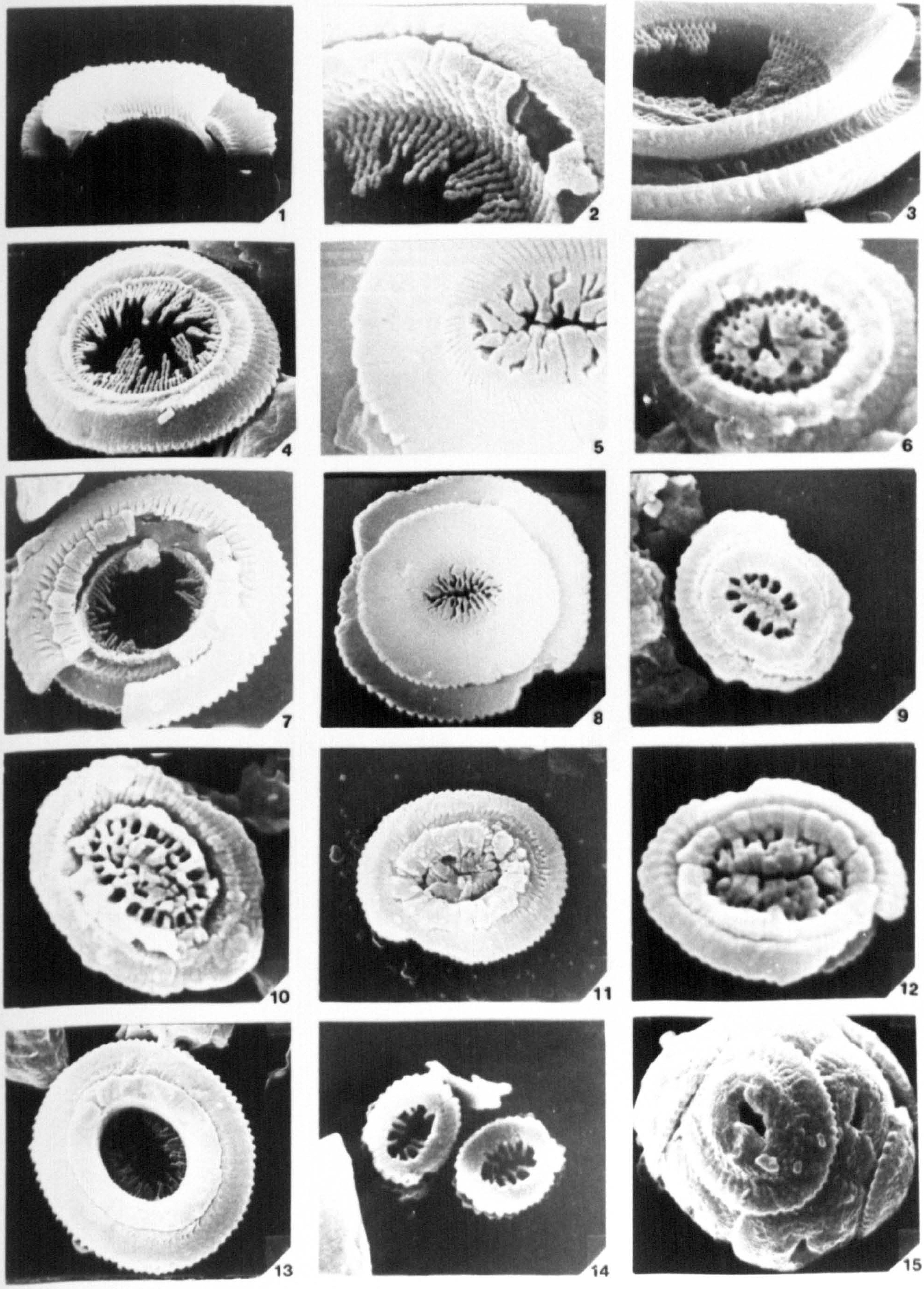
10. Reticulofenestra foveolata (Reinhardt) Roth : UCL-2335-18 distal view of an etched specimen. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene. X7,500.

12. Reticulofenestra foveolata (Reinhardt) Roth : UCL-2349-33 distal view of a slightly overgrown specimen. S136/898. William's Bluff, Oamaru, New Zealand. Early Oligocene. X7,500.

14. Reticulofenestra minuta Roth : UCL-2553-18 proximal views of two specimens. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X7,500.

15. Reticulofenestra pseudoumbilicus (Gartner) Gartner : UCL-2578-19 coccosphere. 9099. Dtrymou, Cyprus. Pliocene. X5,000.

# PLATE i



## PLATE ii : TOWEIUS and RETICULOFENESTRA

1 & 2. Toweius sp. : Fig.1 UCL-2583-28; Fig.2 UCL-2583-19 inner cycle and proximal shield elements with outer cycle elements adpressed against the inner cycle elements. AG16. Pegwell Bay, Kent. Late Palaeocene. X10,000.
3. Toweius pertusus? (Sullivan) Romein : Fig.3 UCL-2583-24 oblique distal view, outer cycle elements seen between the inner cycle elements and the distal shield elements. AG16. Pegwell Bay, Kent. Late Palaeocene. X10,000.
4 & 5. Toweius sp. : Fig.4 UCL-2583-07 side view; Fig.5 UCL-2583-04 oblique distal view. Distal shield absent, structural relationship between inner cycle and proximal shield elements illustrated. AG16. Pegwell Bay, Kent. Late Palaeocene. X10,000.
6. Toweius pertusus? (Sullivan) Romein : UCL-2582-20 oblique distal view, broken distal shield, and remnant of outer cycle seen between inner cycle and distal shield. AG16. Pegwell Bay, Kent. Late Palaeocene. X10,000.
All micrographs X2000 magnification.
7. Reticulofenestra umbilicus (Levin) Martini and Ritzkowski : UCL-2446-34 phase contrast. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene.
8. Reticulofenestra dictyoda (Deflandre) Stradner : UCL-2540-35 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene.
9 & 10. Reticulofenestra scissura Hay, Mohler and Wade : Fig.9 UCL-2202-06 phase contrast; Fig.10 UCL-2202-05 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 6950'. Late Oligocene.
11 & 12. Reticulofenestra reticulata (Gartner and Smith) Roth and Thierstein : Fig.11 UCL-2479-04 phase contrast; Fig.12 UCL-2479-02 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 1288'. Late Eocene.
13 & 14. Reticulofenestra daviesii (Haq) Haq : Fig.13 UCL-2540-23 phase contrast; Fig.14 UCL-2540-24 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene.
15 & 16. Reticulofenestra laevis Roth and Hay : Fig.15 2526-11 phase contrast; Fig.16 UCL-2526-12 crossed-nicols. A57. St. Stephen's Quarry, Alabama, U.S.A. (caved) Early Oligocene.
17 & 18. Reticulofenestra callida (Perch-Nielsen) Bybell : Fig.17 UCL-2254-04 phase contrast; Fig.18 UCL-2254-03 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene.

# PLATE ii

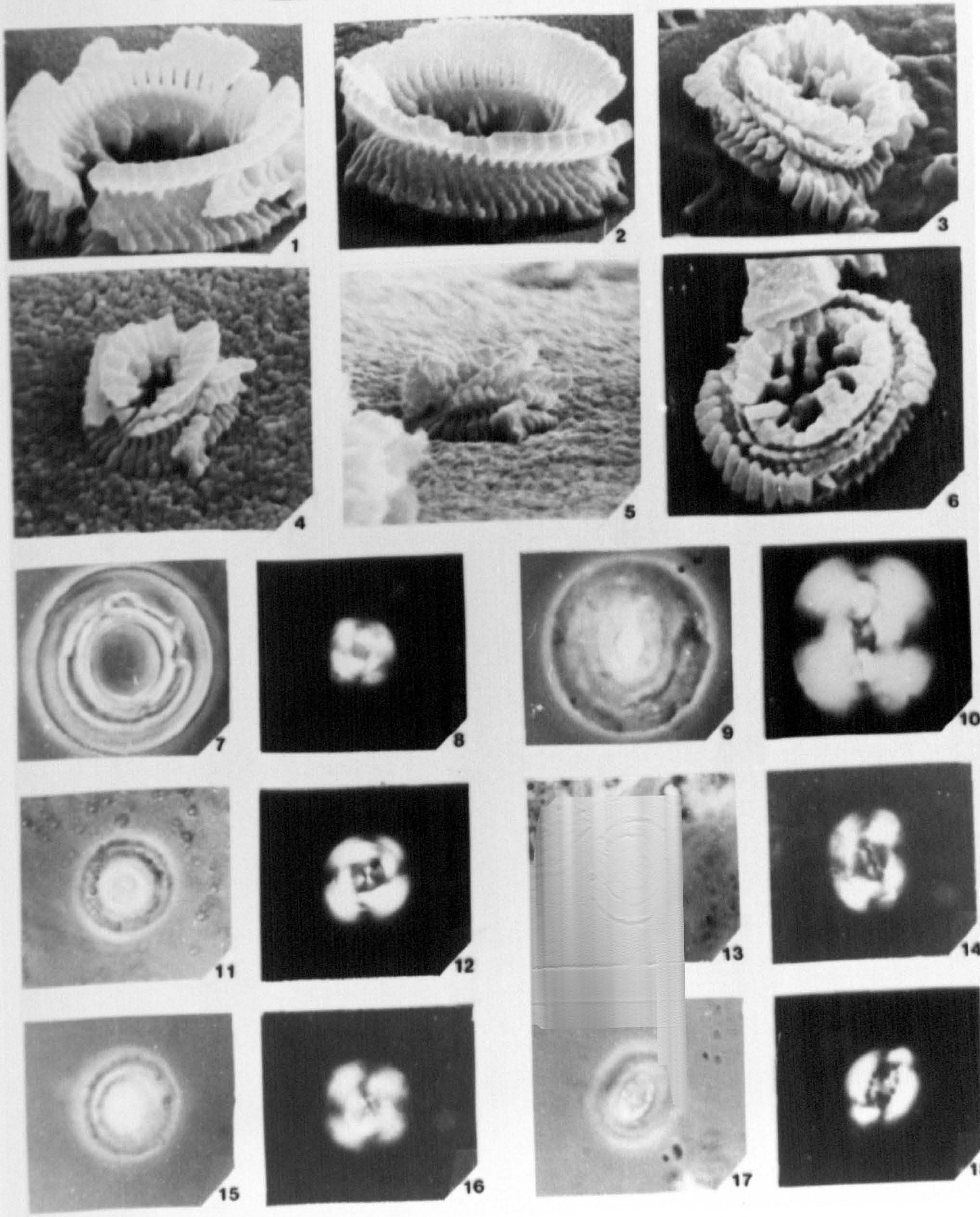
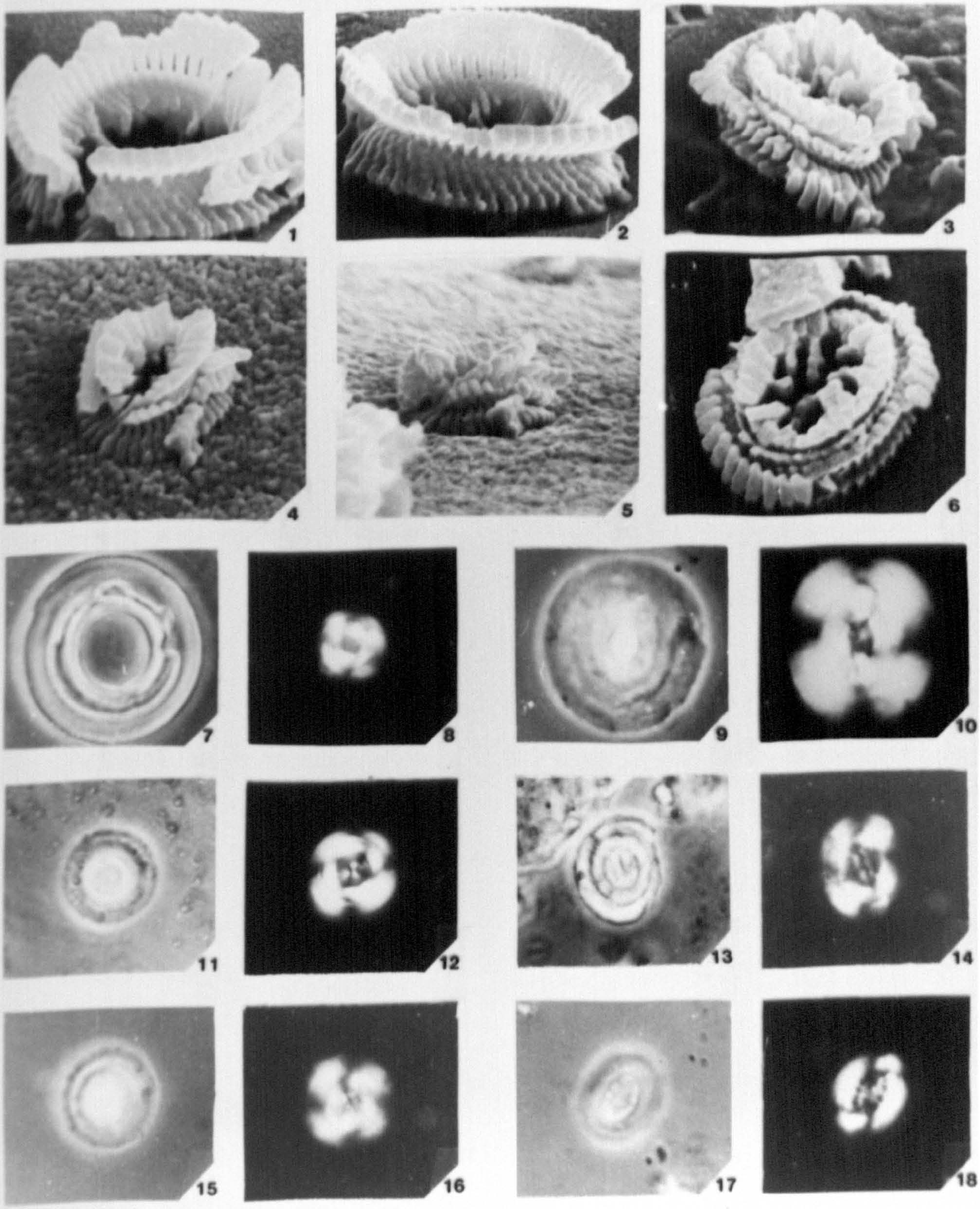


PLATE ii : TOWEIUS and RETICULOFENESTRA

1 & 2. Toweius sp. : Fig.1 UCL-2583-28; Fig.2 UCL-2583-19 inner cycle and proximal shield elements with outer cycle elements adpressed against the inner cycle elements. AG16. Pegwell Bay, Kent. Late Palaeocene. X10,000.
3. Toweius pertusus?(Sullivan) Romein : Fig.3 UCL-2583-24 oblique distal view, outer cycle elements seen between the inner cycle elements and the distal shield elements. AG16. Pegwell Bay, Kent. Late Palaeocene. X10,000.
4 & 5. Toweius sp. : Fig.4 UCL-2583-07 side view; Fig.5 UCL-2583-04 oblique distal view. Distal shield absent, structural relationship between inner cycle and proximal shield elements illustrated. AG16. Pegwell Bay, Kent. Late Palaeocene. X10,000.
6. Toweius pertusus? (Sullivan) Romein : UCL-2582-20 oblique distal view, broken distal shield, and remnant of outer cycle seen between inner cycle and distal shield. AG16. Pegwell Bay, Kent. Late Palaeocene. X10,000.
All micrographs X2000 magnification.
7. Reticulofenestra umbilicus (Levin) Martini and Ritzkowski : UCL-2446-34 phase contrast. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene.
8. Reticulofenestra dictyoda (Deflandre) Stradner : UCL-2540-35 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene.
9 & 10. Reticulofenestra scissura Hay, Mohler and Wade : Fig.9 UCL-2202-06 phase contrast; Fig.10 UCL-2202-05 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 6950'. Late Oligocene.
11 & 12. Reticulofenestra reticulata (Gartner and Smith) Roth and Thierstein : Fig.11 UCL-2479-04 phase contrast; Fig.12 UCL-2479-02 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 1288'. Late Eocene.
13 & 14. Reticulofenestra daviesii (Haq) Haq : Fig.13 UCL-2540-23 phase contrast; Fig.14 UCL-2540-24 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene.
15 & 16. Reticulofenestra laevis Roth and Hay : Fig.15 2526-11 phase contrast; Fig.16 UCL-2526-12 crossed-nicols. A57. St. Stephen's Quarry, Alabama, U.S.A. (caved) Early Oligocene.
17 & 18. Reticulofenestra callida (Perch-Nielsen) Bybell : Fig.17 UCL-2254-04 phase contrast; Fig.18 UCL-2254-03 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene.

# PLATE ii



## 4.5 INVESTIGATION OF CYCLICARGOLITHUS :

Investigation of specimens quoted in the literature revealed some confusion as to what criterion actually separated the two species C. abisectus and C. floridanus, a popular misconception being that the isogyres curve in different directions when the species are viewed under cross-polarised light, and that the isogyres in C. abisectus are disjunct at the margin of the rim and tube cycle:

Table 18 demonstrates conflicting ideas for the structural and optical properties for each of these species i.e. A = (E = G) and (B = F = I = J = K) = (H = D). Criteria which should be used to separate these species are confused, i.e. A = (B =F =I) and C = (B = J = K) and H = (E = G).

Waghorn (1981) investigated these two species, and concluded that they should be separated about a shield diameter of 8.8um (C. abisectus being the larger and C. floridanus the smaller) and that C. abisectus probably developed from C. floridanus by an increase in size in the Late Oligocene.

Measurements of specimens of both species during this study were limited by the resolution of the light and scanning electron microscopes, but values for the overall diameter and the central area opening diameter were computed and analysed as follows :

Each set of figures represents the mean overall diameter followed by the mean central opening diameter. All values are in um's.

| | *C. floridanus* | *C. abisectus* |
|---|---|---|
| Above LOD of *C. abisectus* | 5.1/1.0 | |
| Within the range of *C. abisectus* and *C. floridanus* | 4.9/1.1 | 7.4/1.1 |
| Below FOD of *C. abisectus* | 5.0/1.1 | |

The overall size of *C. floridanus* appeared not to change significantly with the inception and extinction of *C. abisectus*. It is likely that *C. abisectus* is a 'sub-species' of *C. floridanus* (developed during the Late Oligocene) rather than a separate species, as they have identical structural properties and are only distinguishable by a size differential in the population. The fact that the sutures are visible in *C. abisectus* in the LM (cf. Waghorn, 1981, p.41) is merely a function of its size, and the nature of the extinction lines around the tube cycle/rim margin is dependent upon the preservation of the tube cycle. If the 'kinks' in the rim elements (adjacent to tube cycle) are visible then the isogyres will appear continuous; if these 'kinks' are obscured by the tube cycle then the isogyres will appear disjunct. For the sake of biostratigraphical refinement these forms are considered as separate species in this report, but further research is likely to prove that they are conspecific morphotypes.

Table.18 .

| Cyclicargolithus abisectus | Cyclicargolithus floridanus | Author |
|---|---|---|
| A SUTURES clockwise on distal surface. | B ISOGYRES clockwise on distal surface. | Müller, 1970 |
| C ISOGYRES clockwise on distal surface. | D ISOGYRES counter-clockwise on proximal surface. SUTURES counter-clockwise on distal surface. | Bramlette & Wilcoxon, 1967. |
| E SUTURES slightly counter-clockwise on distal surface. | | Bukry & Percival, 1971. |
| | F SUTURES clockwise on distal surface. | Roth & Hay, 1967. |
| G SUTURES counter-clockwise on distal surface. | | Perch-Nielsen 1977. |
| | H SUTURES counter-clockwise on distal surface. | Roth, 1970. |
| | I SUTURES slightly clockwise on distal surface and radial on the proximal surface. | Perch-Nielsen 1972. |
| | J ISOGYRES clockwise on distal surface. | Theodoridis, 1984. |
| | K ISOGYRES clockwise on distal surface. | Locker, 1967 |
| | L ISOGYRES seen to go both clockwise and counter-clockwise; surfaces not stated. | Aubry, 1986. |

# BIOZONATION

INTRODUCTION

BIOSTRATIGRAPHY OF SAMPLE MATERIAL

INTEGRATED BIOZONATION

## 5.1 INTRODUCTION :

It is a generally accepted fact that low latitude calcareous nannofossil assemblages are more diverse than those from high latitudes (e.g. Bukry, 1978). The most diverse and abundant assemblages of Cenozoic calcareous nannofossils, which consequently permit the most detailed biozonation, are found in warm-water areas at low latitudes (40°S - 40°N) and in relatively shallow depths (<4000m), though not nearshore necessarily. Conversely, high latitude, cool-water regions (>4000m in depth), are depleted in density and diversity of calcareous nannofossils (Bukry, 1978) and, hence, are only broadly zonable within the framework of the 'standard' biozonation schemes.

Fewer marker species are thus available for the sub-division of high latitude sections, as clearly demonstrated where attempts have been made to apply the essentially low and middle-latitude biozonation schemes of Martini (1971) and Okada and Bukry (1980) to high latitude sites. (e.g. Martini and Müller, 1973; Aubry, 1983).

'Local' biozonation schemes, utilising calcareous nannofossils, have been erected for various areas in which the 'standard' schemes have been seen to be non-applicable. e.g. New Zealand - Waghorn <u>in</u> Perch-Nielsen, 1985; Stradner and Edwards, 1968; South-west Pacific - Edwards, 1971; Edwards and Perch-Nielsen, 1975; North Atlantic/Norwegian Sea - Müller, 1976; North-west Europe (with some references to the North Sea Basin) - Aubry, 1983, 1985a, 1986; Perch-Nielsen, 1979; Van Heck and Prins, 1987, etc.

Müller (1978) made some of the first observations which could be used to refine the 'standard' zonations to fit a northern hemisphere locality (with particular emphasis on the Palaeogene). In 1979 Perch-Nielsen published a zonation scheme for the Danian of Denmark, which was also tested and found to be applicable to the North Sea Basin, although not outside this general area. Her scheme introduced 10 zones within the Early Palaeocene, where only 3 had been recognised by Martini (1971). Most recently O'B Knox (1984), Aubry (1985a, 1986), Steurbaut and Nolf (1986), Köthe (1986), Siesser et al. (1987) and Steurbaut (1988) have all published observations which include alterations and refinements to the ranges of calcareous nannofossils and their zonation in the north-west European area. In particular, Steurbaut (1988) recognised 14 zones within the Early Eocene of the Belgian Basin, where the 'standard' scheme of Martini (1971) contains only 4. Nevertheless Martini's (1971) zonation continues to be used as a primary reference.

Despite the high latitude location of north-west Europe and the North Sea Basin; and diversity reduction at higher latitudes, recent work has shown that it is not only possible to recognise (broadly) the 'standard' zones defined in lower latitude material, but to refine them and increase their utility.

Published work on calcareous nannofossils relating specifically to the North Sea Basin is scarce. Martini and Müller (1973) looked at some Neogene assemblages and compared their constituents to those found in northern Germany. Not until Van Heck and Prins (1987) published a very detailed zonation of the Early Palaeocene was there a comprehensive analysis of Tertiary calcareous nannofossils from the North Sea Basin. They sub-divided the "Danian" into 9 zones (2 of which were further divided into 3 sub-zones each). The strong speciation of calcareous nannofossils after the terminal Cretaceous 'event', with the appearance of numerous new taxa make this refined zonation possible. The use of successive species of an evolutionary lineage and their intermediates to characterise certain intervals does produce a more reliable zonation than one based solely on first occurrences (FOD's or LDO's). It is assumed that no LOD's (or FDO's) were used because few of the species that evolved in the Early Palaeocene actually became extinct before the Late Palaeocene (outside the range of the zonation).

Kok (unpub.) investigated Palaeogene calcareous nannofossil assemblages from the central and southern North Sea Basin and produced an outline biozonation scheme which he correlated with the chronostratigraphy and other zonation schemes. The present study extended the work of Kok into the Neogene and is an attempt to refine the biostratigraphy of the whole of the Tertiary using calcareous nannofossils, and to produce a viable biozonation scheme.

## 5.2 BIOZONATION OF THE CENTRAL AND SOUTHERN NORTH SEA BASIN USING CALCAREOUS NANNOFOSSILS :

When dealing with material from exploration wells (particularly DC's) there is always the possibility of contaminants affecting the calcareous nannofossil assemblages recovered. Contamination can take the form of 're-working' (e.g. Cretaceous and Danian forms within the Maureen Formation) which may be 'primary' and occurred during deposition of the sediment, or 'secondary', as a result of some drilling process. Another form of contamination, one which has a greater effect on the age assignment of a recovered assemblage, is 'caving'. Caving is particularly prevalent in DC's and results from the downward migration of chippings through the drilling mud, as they are brought to the surface, thus giving anomalous lowest occurrences. Even SWS's can be contaminated by the drilling mud, or by coming into contact with the wall of the well on their way to the surface (although cleaning before analysis minimises these effects).

With these problems (inherent in well material) in mind this zonation was based primarily on FDO's of species (reliable and accurate as they are not affected by caving) in association with the general assemblage present and leaving in mind the possibility of natural upsequence reworking.

As drilling and analysis of well material traditionally proceeds from young to old strata, the numbering of zones follows this direction.

### 5.2.1 CALCAREOUS NANNOFOSSIL BIOZONATION OF THE TERTIARY OF THE NORTH SEA BASIN, AND CORRELATION WITH COMPARATIVE SECTIONS :

Fig.45. is a diagrammatic representation of the calcareous nannofossil zonation scheme for the central and southern North Sea Basin, as proposed in this study. A full description and discussion of each zone follows detailing the marker species, the correlation with established zonation schemes, and remarks concerning relationships with comparative onshore material, etc.

#### HELICOSPHAERA SELLII ZONE
#### (NS1)

Author : Described herein.

Definition : This zone is represented by the interval bounded by the FDO of Helicosphaera sellii and the FDO of Reticulofenestra pseudoumbilicus.

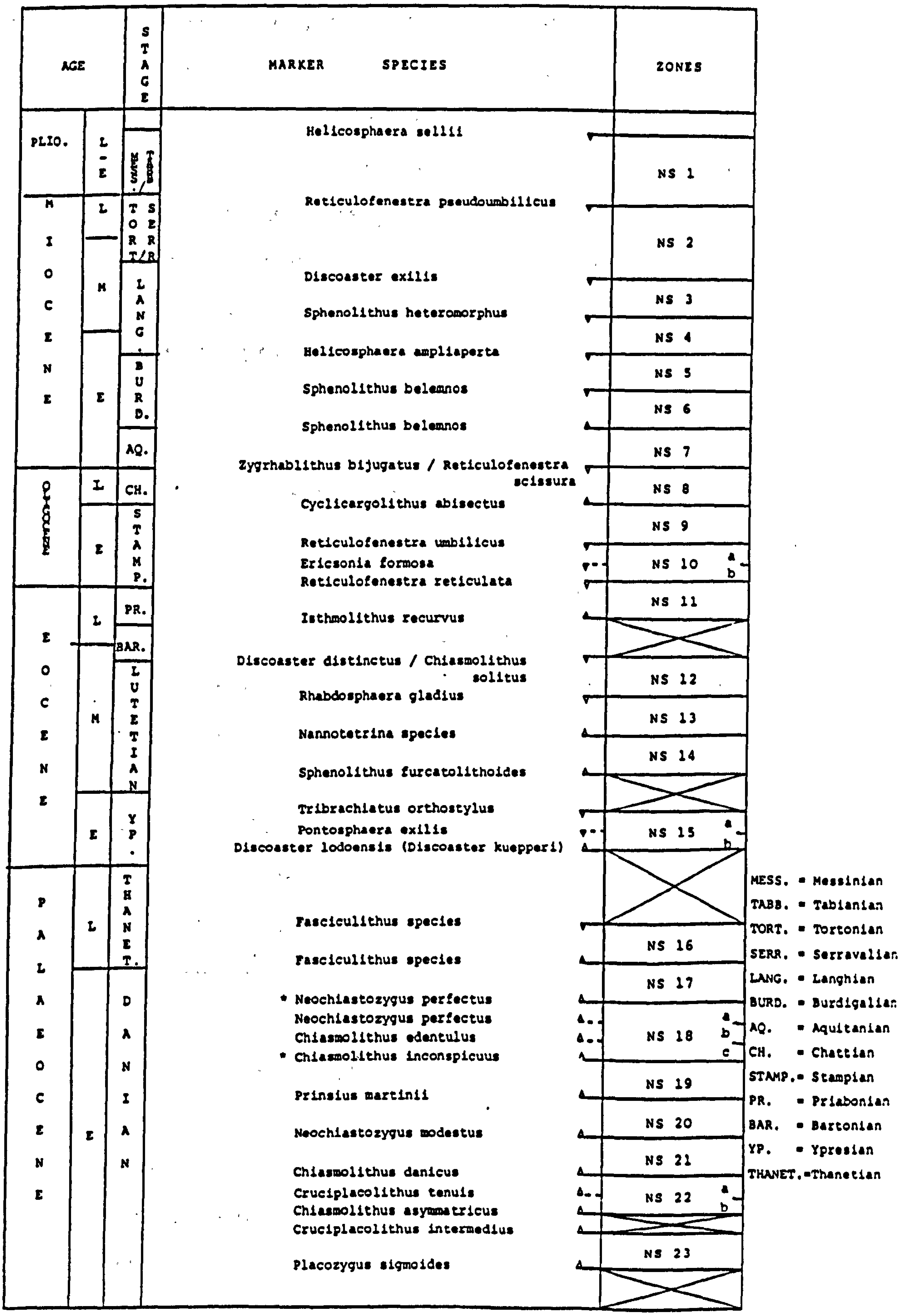
Age : Pliocene ?

Reference : Well number 30/19-2, 3510' - 3900'.

Correlation : A very general (in terms of age assignment) zone which can be approximately correlated with the NP15-18 zones of Martini (1971) and probably the 'sellii assemblage' (Pliocene) of Martini and Müller (1973).

FIG. 45.

CALCAREOUS NANNOFOSSIL BIOZONATION OF THE TERTIARY OF THE NORTH SEA BASIN




* = common occurrence
NS = North Sea

= FDO
= LDO

Remarks : The whole of the Middle and Late Miocene and the Pliocene was zoned by Martini almost exclusively by the FDO's or LDO's of Discoaster species. As none of these markers except D. exilis was present in the North Sea Basin, the zonation of the upper intervals in certain wells was problematical and very generalised. The occurrence of H. sellii in sparse assemblages above the FDO of R. pseudoumbilicus was taken to indicate a broad Pliocene age.

## RETICULOFENESTRA PSEUDOUMBILICUS ZONE
## (NS2)

Author : Described herein.

Definition : Interval between the FDO of Reticulofenestra pseudoumbilicus and the FDO of Discoaster exilis.

Age : Late Miocene.

Reference : Well number 29/10-1, 4200' - 4780'.

Correlation : This zone is also very general in terms of its biostratigraphical refinement, but can be approximately correlated with the NP7-12 zones of Martini (1971).

Remarks : R. pseudoumbilicus in association with a general assemblage including Calcidiscus rotula, Calcidiscus macintyrei, Reticulofenestra perplexa, Calcidiscus leptoporus, Reticulofenestra minutula and Helicosphaera carteri was used to identify a Late Miocene zone within the sediment pile.

## DISCOASTER EXILIS ZONE
## (NS3)

Authors : In part after Martini and Worsley (1970) (the lower boundary) and name of the zone, and Okada and Bukry (1980) (the upper boundary).

Definition : The zone lies within the FDO of Discoaster exilis and

Cyclicargolithus floridanus (top) and the FDO of Sphenolithus heteromorphus (base).

Age : Middle Miocene.

Reference : Well number 29/10-1, 4780' - 5530'.

Correlation : The Discoaster exilis zone (NS3) as defined herein is approximately equivalent to the Discoaster exilis Zone (NN6) of Martini (1971). The base of the zone correlates exactly, but the top of the zone, in the absence of Discoaster kugleri, is defined by the FDO of Cyclicargolithus floridanus. The zone is approximately equivalent to the Coccolithus miopelagicus sub-zone of Bukry (1978) in terms of the boundary species.

Remarks : Many of the species cited by Martini (1971) and Okada and Bukry (1980), in particular some of the Discoaster species, are absent from the North Sea Basin material examined.

## SPHENOLITHUS HETEROMORPHUS ZONE

## (NS4)

Authors : Bramlette and Wilcoxon (1967).

Definition : The upper boundary is set at the FDO of Sphenolithus heteromorphus and the lower boundary is set at the FDO of Helicosphaera ampliaperta.

Age : Middle Miocene.

Reference : Well number 29/10-1, 5530' - 5610'.

Correlation : This zone correlates exactly with the Sphenolithus heteromorphus zone (NN5) as defined by Martini (1971), and represents one of only a few horizons in the North Sea Basin which can be so accurately correlated.

Remarks : Sphenolithus heteromorphus is a readily identifiable and consistent constituent of the Middle Miocene of the North Sea Basin, and can be used as a marker species.

### HELICOSPHAERA AMPLIAPERTA ZONE

### (NS5)

Authors : Bramlette and Wilcoxon (1967) emend. Martini (1971).

Definition : Interval from the FDO of Helicosphaera ampliaperta to the FDO of Sphenolithus belemnos.

Age : Early Miocene.

Reference : Well number 29/10-1, 5610' - 5790'.

Correlation : This zone also correlates exactly to that defined by Martini (1971) ( Helicopontosphaera ampliaperta zone, NN4).

Remarks : Helicosphaera ampliaperta is a consistent member of the calcareous nannofossil assemblage throughout the Early Miocene, and distinctive enough to prove a useful marker species. Both this and the preceding zone were broadly recognised by Martini and Müller (1973) from the North Sea area.

### SPHENOLITHUS BELEMNOS ZONE

### (NS6)

Author : Bukry (1973) emend. Bukry (1975).

Definition : This zone is defined by the total range of Sphenolithus belemnos (FDO to LDO).

Age : Early Miocene.

Reference : Well number 21/11-1, 2390' - 2410'.

Correlation : Although the upper boundary corresponds to that used by Martini (1971) the lower boundary differs due to the absence of Triquetorhabdus carinatus from the study material. The zone is in fact directly correlatable with the CN2 zone of Okada and Bukry (1980) which uses the same boundary criteria.

Remarks : Müller (1979) recognised this zone in the North Atlantic. It is normally represented by a relatively thin unit of sediment, but is readily identifiable by the presence of the distinctive species Sphenolithus belemnos in association with Helicosphaera ampliaperta.

## HELICOSPHAERA MEDITERRANEA ZONE
## (NS7)

Author : Defined herein.

Definition : Interval between the LDO of Sphenolithus belemnos and the FDO of Reticulofenestra scissura.

Age : Early Miocene.

Reference : Well number 21/11-1, 2410' - 2440'.

Correlation : This zone does not correlate with any of the established zones (e.g. Martini, 1971; Okada and Bukry, 1980) due to a lack of distinctive marker species. Perch-Nielsen (1985a) and Müller (1979) indicate that it is difficult to sub-divide zones NN1-NN3 in high latitude sites. This zone approximately corresponds to the NN1 and NN2 zones of Martini (1971).

Remarks : It is recognised by the co-occurrence of Helicosphaera ampliaperta, Helicosphaera carteri and the distinctive, though uncommon, Helicosphaera mediterranea. It may be possible to sub-divide this zone on the LDO of Helicosphaera ampliaperta in material containing adequate SWS's. The assemblage is commonly low in diversity and may contain specimens re-worked from lower levels. Assemblages below the LDO of H. ampliaperta could not be satisfactorily differentiated in any of the well material.

The Miocene / Oligocene boundary was difficult to accurately determine in the study material because of 'mixed' assemblages occurring for some distance above and below the supposed boundary, and because it was within a monotonous sediment unit (Hordaland Formation) with no obvious lithological breaks.

## ZYGRHABLITHUS BIJUGATUS ZONE
## (NS8)

Author : Defined herein.

Definition : This zone is bounded by the FDO of Reticulofenestra scissura and Zygrhablithus bijugatus and the LDO of Cyclicargolithus abisectus.

Age : Late Oligocene.

Reference : Well number 21/30-1, 5202' - 5700'.

Correlation : In terms of the 'standard' zonation schemes, this zone is approximately equivalent to the NP24/25 zones of Martini (1971) and the CP19 zone of Okada and Bukry (1980).

Remarks : The absence of the established Sphenolithus marker species (S. ciperoensis [very rare], S.predistentus, and S. distentus) from the North Sea Basin material made the sub-division of the Late Oligocene very difficult. Kok (unpub.) recognised only a single zone between the FDO of Zygrhablithus bijugatus and the FDO of Reticulofenestra umbilicus, and Müller (1979) remarked that sub-division of the Middle/Upper Oligocene is often impossible in such high latitude sites. The boundary between the NP24 and NP25 zones has been put at the LDO of Pontosphaera enormis (Müller, 1978), but the very rare occurrence of this species within the study material made its use as a marker species impracticable. Waghorn in Perch-Nielsen (1985) used the FDO of Chiasmolithus altus to separate the Discoaster deflandrei zone from the Cyclicargolithus abisectus zone (an approximation to the NP24 - NP25 separation). In the study material C. altus was found to be a very distinctive component of the Late Oligocene calcareous nannofossil assemblage (in association with Zygrhablithus bijugatus, Cyclicargolithus abisectus, and Helicosphaera recta) and in the wells in which it occurred there was a slight differential between it's FDO and the FDO of Reticulofenestra scissura. This indicates potential for sub-dividing this zone, however, a greater concentration of samples (preferably SWS's) from relevant levels in more wells would have to be analysed before this could be satisfactorily demonstrated. Despite the potential for caving, the LDO of C. abisectus was determinable in a number of wells (not 29/10-1, where caving did obscure this datum) and used to define the base of this interval (as in Waghorn in Perch-Nielsen, 1985).

Samples analysed from the Rockall Basin and the South Atlantic Ocean showed a remarkable similarity with the assemblages recovered from the North Sea Basin; the common factors being a lack of Sphenolithus marker species and an abundance of Chiasmolithus altus.

## RETICULOFENESTRA SCISSURA ZONE

## (NS9)

Author : Defined herein.

Definition : Interval from the LDO of Cyclicargolithus abisectus to the FDO of Reticulofenestra umbilicus.

Age : Early/Late Oligocene.

Reference : Well number 21/11-1, 2820' - 2840'.

Correlation : Approximates to the NP23 zone of Martini (1971) and the CP17/18 zones of Okada and Bukry (1980).

Remarks : As remarked by Perch-Nielsen (1985, p.441) the only way to distinguish this zone, in high latitude material such as that in the North Sea

Basin, is on the basis of the presence of Reticulofenestra scissura and the absence of both Cyclicargolithus abisectus and Reticulofenestra umbilicus. This zone was extremely difficult to accurately locate due to the nature of the sample material.

### RETICULOFENESTRA UMBILICUS

### (NS10)

Authors : Bramlette and Wilcoxon emend. Martini (1970).

Definition : Interval between the FDO of Reticulofenestra umbilicus and the FDO of Reticulofenestra reticulata.

Age : Early Oligocene.

Reference : Well number 21/11-1, 2840' - 3120'.

Correlation : This zone approximates to the NP21/22 zones of Martini (1971) and it is based on the same upper boundary event.

Remarks : The zone has Isthmolithus recurvus, Lanternithus minutus, Ericsonia formosa, and Ericsonia subdisticha common within it, as does the NP21/22 zones of Martini (1971). This zone, indeed the whole of the Early Oligocene, was poorly represented in the study material, and only identified on the basis of successive FDO's within a series of DC's. It is possible that more detailed investigation will allow a sub-division of this zone on the basis of the FDO of Ericsonia formosa occurring above the FDO of Reticulofenestra reticulata (events which are coincident in the present study material), thus separating the equivalent of the NP22 zone from one approximating to NP21.

Samples analysed from Alabama and from JOIDES 5 (low latitude localities) yielded significantly different Early Oligocene calcareous nannofossil assemblages from those found in the North Sea Basin; assemblages more comparable with those of the 'standard' zonation schemes (see Chapter 3).

## ISTHMOLITHUS RECURVUS ZONE

## (NS11)

Authors : Upper boundary : Müller (1979), lower boundary : Martini (1971). emend Aubry (1983).

Definition : Interval from the FDO of Reticulofenestra reticulata to the LDO of Isthmolithus recurvus.

Age : Late Eocene.

Reference : Well number 49/9-1, 1288' - 1470' (1650' ?).

Correlation : This zone can be correlated with the NP19/20 zones of Martini (1971) as re-combined by Aubry (1983).

Remarks : The usual calcareous nannofossil event used to mark the Eocene/Oligocene boundary is the FDO of the 'rosette-shaped' discoasters (Discoaster saipanensis, and Discoaster barbadiensis), however, although they are present in the study material, their FDO's were not always synchronous or consistent and they are not used. The FDO of Reticulofenestra reticulata was found to be a consistent event in the study material and, in association with Isthmolithus recurvus, could be used to define this interval (Aubry, 1983 p.152, proposed the FDO of R. reticulata as a secondary marker for the NP19/20 interval; Müller, 1978 p.48-49, proposed it as a marker for the Eocene/Oligocene boundary in high latitudes). The LDO of I. recurvus was identifiable in sections containing SWS's, but the species is very susceptible to caving and its LDO in a DC interval is unreliable. Sub-division of this zone using the established marker species Sphenolithus pseudoradians has been known to be unreliable for some time (see Aubry, 1983, p.41-42), thus the interval has remained a combination of two zones. Waghorn in Perch-Nielsen (1985) used the LDO of Reticulofenestra oamaruensis to approximate to the base of the NP20 zone (unfortunately this species did not occur in the study well material) and the FDO of R. reticulata to approximate to the top of the NP19 zone, an event which has already been applied to the top of the equivalent to the combined NP19/20 zone.

In the Alabama section studied, the top of the Eocene (NP20) was clearly demarcated by the LOD (=FDO) of Discoaster saipanensis and Discoaster barbadiensis (species which were present but rare and with patchy occurrences in the North Sea Basin material). The sample from William's Bluff in New Zealand (S136/898) was also dated as Late Eocene (NP19/20), but the assignment was based on the association of Discoaster saipanensis, Isthmolithus recurvus and Reticulofenestra oamaruensis. At the top of the section at Hampden Beach, New Zealand (HB772) the assemblage of calcareous nannofossils was equivalent in age to Martini's (1971) NP19 zone based on the FOD of Isthmolithus recurvus in association with Reticulofenestra reticulata (- a similar association to that seen in the North Sea Basin).

Assemblages equivalent in age to Martini's (1971) NP17/18 zones were not recovered from the North Sea Basin, although the possibility of finding such assemblages is not discounted (see Chapter 2 for discussion). Sections of this age were analysed from Alum Bay on the Isle of Wight (Hampshire Basin) and from the Hampden Beach area of New Zealand.

## CHIASMOLITHUS SOLITUS ZONE
## (NS12)

Authors : Hay et al. (1967) emend. Martini (1970) under the name Discoaster tanii nodifer zone.

Definition : Interval bounded by the FDO of Chiasmolithus solitus or Discoaster distinctus and the FDO of Rhabdosphaera gladius.

Age : Middle Eocene.

Reference : Well number 49/9-1, 1535' - 1737'.

Correlation : This zone is approximately equivalent to the NP16 zone of Martini (1971).

Remarks : The use of Discoaster distinctus as an alternative to Chiasmolithus solitus was suggested by Aubry (1983, p.41). In the study material both species were present, but D. distinctus tended to have a higher FDO than C. solitus, and was thus used more often to locate the upper boundary. Discoaster bifax (also suggested by Aubry op. cit. as an alternative marker species for the upper boundary) had a much more sporadic occurrence and could not be applied biostratigraphically. Assemblages approximately equivalent in age to the NS12 zone were recovered from the Isle of Wight sections and from the Hampden Beach section in New Zealand, although they were less well defined (see chapter 3 for discussion).

## RHABDOSPHAERA GLADIUS ZONE
## (NS13)

Authors : Hay in Hay et al. (1967) emend. Martini (1970) under the name Nannotetrina fulgens zone.

Definition : Interval from the FDO of Rhabdosphaera gladius to the LDO of Nannotetrina species.

Age : Middle Eocene.

Reference : Well number 49/9-1, 1737' - 2130'.

Correlation : This zone correlates very closely to the NP15 zone of Martini (1971).

Remarks : The lower boundary of this zone is taken at the LDO of all Nannotetrina species, instead of Nannotetrina fulgens, because of the relative rarity of these forms in the study material, and the fact that there is some taxonomic confusion as to their exact affinities (see Perch-Nielsen, 1985, p.439 for further discussion). The distinctive nature of Rhabdosphaera gladius meant that this zone was usually readily identifiable, albeit in only a small number of the wells studied. The marker species of this zone were also found in assemblages from Whitecliff Bay, Isle of Wight and from the lower part of the Hampden Beach Formation (HB728-748) in New Zealand which were dated as equivalent to the NP15 zone of Martini (1971).

**SPHENOLITHUS FURCATOLITHOIDES ZONE**

**(NS14)**

Author : Described herein.

Definition : Interval between the LDO of Nannotetrina species and the FDO of Sphenolithus furcatolithoides.

Age : Early/Middle Eocene.

Reference : Well number 49/9-1, 2130' - 2490'.

Correlation : This zone is approximately equivalent to the upper part of the NP14 zone of Martini (1971) and Units XII and XIII (basal Lutetian) of Steurbaut and Nolf (1986) and Steurbaut (1988), based on the LDO of S. furcatolithoides.

Remarks : The absence of Discoaster sublodoensis from the North Sea Basin study material made the sub-division of an already impoverished assemblage virtually impossible using calcareous nannofossils. The LDO's of Chiasmolithus expansus, Discoaster saipanensis, Pontosphaera wechesensis, and Birkelundia staurion are also noted in this interval. The assemblage recovered from Sample I46 (Whitecliff Bay, Isle of Wight) was dated as equivalent to the NP14/15 zone of Martini (1971) and may, therefore, be approximately correlated with the NS14 zone.

Assemblages equivalent to the NP13 zone of Martini (1971) and representing part of the Early Eocene succession were not recognised in terms of calcareous nannofossils in any of the sample material, although foraminifera were recovered from the North Sea Basin (see discussions in Chapter 2).

## TRIBRACHIATUS ORTHOSTYLUS ZONE

## (NS15)

Authors : Bronniman and Stradner (1960).

Definition : This zone is bounded by the FDO of Tribrachiatus orthostylus and the LDO of Discoaster lodoensis (or the LDO of common Discoaster kuepperi).

Age : Early Eocene.

Reference : Well number 29/7-1, 7901' - 8030'.

Correlation : As defined in Martini (1971) the NP12 zone is an exact equivalent of this zone in terms of marker species, but the assemblage described by Martini (1971) is not fully represented in the North Sea study material.

Remarks : Aubry (1983, 1986) suggested the use of the LDO of D. kuepperi as a replacement for the LDO of D. lodoensis in sections where the latter was poorly represented. In the North Sea Basin D. kuepperi was seen to be a useful secondary marker species, where it was associated with the less common, but nevertheless usable, D. lodoensis.

The presence of Pontosphaera exilis in these assemblages may indicate the earliest NP12 zone only, as it has a FDO corresponding to the top of Unit IV of Steurbaut (1988). It is therefore possible, given further research, that the NS15 zone determined herein may be sub-divided on the presence/absence of Pontosphaera exilis.

Assemblages recovered from the London Clay Formation and Wittering Formation on the Isle of Wight contained poorly preserved specimens which could only be dated as equivalent to the NP11/12 zones of Martini (1971). Discoaster lodoensis was absent from these onshore sections, but the NP12 zone was assigned on the basis of the common occurrence of Discoaster kuepperi. The London Clay Formation of the London Basin yielded better preserved assemblages of calcareous nannofossils which could be dated as NP12 zone of Martini (1971) or Unit V of Steurbaut (1988) on the basis of the common occurrence of Discoaster kuepperi and the absence of Pontosphaera exilis, and NP11 zone of Martini (1971) where Discoaster kuepperi was absent. It would appear that the NS15 zone correlates with an age between that of the samples analysed from the London Basin.

The Late Palaeocene, almost in entirety, was not represented in terms of calcareous nannofossil assemblages from the North Sea Basin study material. This information gap approximated to zones NP6 - NP11 of Martini (1971). Foraminiferal data was used to cover much of this 'barren' interval (see discussion in Chapter 6). Assemblages of NP8 zone were analysed from the Pegwell Bay area of Kent (see Chapter 3 for discussion), but these were biostratigraphically isolated from all other sample material.

**FASCICULITHUS TYMPANIFORMIS ZONE**

**(NS16)**

Author : Martini (1971) part, emend. here.

Definition : The FDO of Fasciculithus species, in particular Fasciculithus tympaniformis, to the LDO of Fasciculithus species.

Age : Late Palaeocene.

Reference : Well number 30/6-2, 9700' - 9720'.

Correlation : This very restricted zone (in terms of spatial occurrence) can be approximated to the NP5 (Fasciculithus tympaniformis zone) of Martini (1971), although the upper boundary is different.

Remarks : It is probable that this zone only represents the lower part of the similarly named zone of Martini (1971) as the upper marker species of Martini (1971) were not found anywhere in the basin, and the top of the zone as recognised herein is taken at a sudden influx of a number of species after a barren interval, rather than at a change in the assemblage.

**NEOCHIASTOZYGUS PERFECTUS ZONE**

**(NS17)**

Authors : Van Heck and Prins (1987).

Definition : Interval between the LDO of Fasciculithus species and the LDO of common Neochiastozygus perfectus.

Age : Early Palaeocene.

Reference : Well number 21/11-1, 5220' - 5310'.

Correlation : Equivalent to the N. perfectus zone of Van Heck and Prins (1987) and the S1/S2 zones of Perch-Nielsen (1979).

Remarks : Van Heck and Prins (1987) also used the LDO of large Towelus species to identify the base of this zone. In the study material it was noted that Towelus tovae and Towelus eminens were most abundant within this zone.

The use of LDO's (almost exclusively) in the Palaeocene part of this zonation is justified by the fact that a lot more SWS's were analysed in this part of the wells and by the fact that inceptions of species (FOD = LDO) far outnumber FDO's during the Early Palaeocene as a result of the high speciation rate following the Cretaceous/Tertiary boundary extinction event.

## CHIASMOLITHUS INCONSPICUUS ZONE

## (NS18)

Authors : Van Heck and Prins (1987).

Definition : Interval between the LDO of common Neochiastozygus perfectus and the LDO of common Chiasmolithus inconspicuus. The lower boundary may also be marked by the LDO's of Towelus pertusus and Ericsonia subpertusa.

Age : Early Palaeocene.

Reference : Well number 21/30-1, 6690' - 6850' (upper); 49/9-1, 2658' - 2680' (middle); 49/9-1, 2681' - 2698' (lower).

Correlation : Equivalent to the Chiasmolithus inconspicuus zone of Van Heck and Prins (1987) with the additional lower boundary marker species.

Remarks : The virtual absence of Ellipsolithus macellus form the study material meant that a substitute marker event had to be found for the equivalent of the NP3/NP4 boundary. Van Heck and Prins (1987) chose the 'common' occurrence of C. inconspicuus, which can be supplemented by the LDO's of T. pertusus, E. subpertusa and Prinsius bisulcus.

The C. inconspicuus Zone (NS18) can be sub-divided using the same criteria as Van Heck and Prins (1987); that is the LDO of Neochiastozygus perfectus for the upper part and the LDO of Chiasmolithus edentulus for the middle part.

## NEOCHIASTOZYGUS SAEPES ZONE

## (NS19)

Authors : Van Heck and Prins (1987).

Definition : This zone is bounded by the LDO of common Chiasmolithus inconspicuus and the LDO of Prinsius martinii.

Age : Early Palaeocene.

Reference : Well number 29/7-1, 8541' - 8570'.

Correlation : Equivalent to the N. saepes zone of Van Heck and Prins (1987), but lacking the full assemblage of species quoted, in particular the LDO of N. saepes was not found to be reliable in this study. This interval is approximately correlated with the D8 and part of the D9 zone of Perch-Nielsen (1979).

Remarks : In the study material this zone could be recognised by the numerical dominance of Chiasmolithus danicus over Chiasmolithus inconspicuus. Not as much emphasis was put on this quantitative analysis as in Van Heck and Prins (1987) due to the gross similarity of these species, particularly in the poorly preserved assemblages studied. N. saepes was rare or absent from assemblages interpreted as of this age in parts of the North Sea Basin.

## NEOCHIASTOZYGUS MODESTUS ZONE

## (NS20)

Authors : Van Heck and Prins (1987).

Definition : Interval between the LDO of Prinsius martinii and the LDO of Neochiastozygus modestus.

Age : Early Palaeocene.

Reference : Well number 30/19-2, 9096' - 9152'.

Correlation : Equivalent to the zone of Van Heck and Prins (1987), and correlated with the D7 zone of Perch-Nielsen (1979) and the middle part of the NP3 zone of Martini (1971).

Remarks : The association of Chiasmolithus danicus, Chiasmolithus inconspicuus, and Neochiastozygus modestus was used to identify this zone in the study material.

## CHIASMOLITHUS DANICUS ZONE

## (NS21)

Authors : The upper boundary was defined by Van Heck and Prins (1987), the lower boundary by Martini (1971).

Definition : This zone is taken as the interval between the LDO of Neochiastozygus modestus and the LDO of Chiasmolithus danicus.

Age : Early Palaeocene.

Reference : Well number 14/29-1, 6300' - 6400'.

Correlation : This zone was approximately correlated with the C. danicus zone of Van Heck and Prins (1987) and the D5/D6 zones of Perch-Nielsen (1979). This zone was also correlated with the earliest part of NP3 zone of Martini (1971).

Remarks : Prinsius dimorphosus was numerically dominant in assemblages assigned to this zone, and associated with minor occurrences of Cruciplacolithus tenuis, Cruciplacolithus intermedius, and Chiasmolithus danicus.

## CRUCIPLACOLITHUS ASYMMETRICUS ZONE

## (NS22)

Authors : Van Heck and Prins (1987) emend. here

Definition : This zone was bounded by the LDO of Chiasmolithus danicus and the LDO of Chiasmolithus asymmetricus.

Age : Early Palaeocene.

Reference : Well number 14/29-1, 6400' - 6450' and well number 30/19-2, 9153' - 9180'.

Correlation : Equivalent to the zone of Van Heck and Prins (1987) except that the upper boundary is set at the LDO of C. danicus, instead of at the LDO of the much rarer and less consistent Chiasmolithus edwardsii.

Remarks : In the study material the absence of C. danicus from an assemblage containing abundant Prinsius dimorphosus, and minor occurrences of Cruciplacolithus tenuis and Cruciplacolithus intermedius was used to indicate the change from the equivalent of Martini's (1971) NP3 zone to the equivalent of his NP2 zone. The presence of C. tenuis in such assemblages indicated that the upper part of the C. asymmetricus zone was present.

No assemblages of an age equivalent to the early part of Martini's (1971) NP2 zone (= C. intermedius zone of Van Heck and Prins, 1987; = D3/D4 zones of Perch-Nielsen, 1979) were recovered from the study material.

## PLACOZYGUS SIGMOIDES ZONE

## (NS23)

Authors : Van Heck and Prins (1987).

Definition : Interval between the LDO of Cruciplacolithus intermedius and the LDO of Placozygus sigmoides.

Age : Early Palaeocene.

Reference : Well number 30/19-2, 9181' - 9206'.

Correlation : Equivalent to the P. sigmoides Zone of Van Heck and Prins (1987), the D2 zone of Perch-Nielsen (1979) and the upper part of the NP1 zone of Martini (1971).

Remarks : A very sparse assemblage containing only small Prinsius species and P. sigmoides was representative of this zone in the study material. Although such an assemblage undoubtedly represented an NP1 assemblage, and was therefore basal Tertiary, it is thought that further investigation of other wells would reveal slightly older assemblages.

None of the wells studied yielded assemblages of an earliest NP1 age (Martini, 1971), equivalent to the B. sparsus zone of Van Heck and Prins (1987) and the D1 zone of Perch-Nielsen (1979), and representative of the earliest Tertiary.

## 6.1 DISCUSSION OF THE CALCAREOUS NANNOFOSSIL BIOZONATION OF THE NORTH SEA BASIN WITH RESPECT TO THE STANDARD TERTIARY STAGES OF THE NORTH-WEST EUROPEAN AREA :

The lithostratigraphy of the North Sea Basin (see Chapter 1) is referred to in terms of Formation names (e.g. Balder, Sele, Lista Formation) which represent 'packets' of sediment indicative of a particular depositional event or a particular sedimentological association. Onshore, however, the Tertiary sediments have been referred to for many years by their Stage names (e.g. Thanetian, Ypresian, Lutetian, etc.) which represent groups of formations linked by common palaeontological and/or sedimentological criteria and age. By comparing the calcareous nannofossil assemblages recovered from the North Sea Basin during this study with those found by previous authors and in this study from onshore sites of north-west Europe, a direct correlation can be developed.

King (1983) recognised that in the North Sea Basin the diversity of planktonic organisms was reduced due to its limited connections with open oceanic areas. Onshore sections tend to have rare or non-diagnostic assemblages, (although Danian and Eocene assemblages in Denmark are exceptionally abundant) due to the nearshore environment of deposition of many of the marine units. In the offshore assemblages, however the distribution of taxa may be irregular due to preservational and sampling effects, but the assemblages are often more diverse and more abundant, and can provide critical additional information.

### 6.1.1 Nordland Group :

The youngest sediment in the North Sea Basin is that of the Nordland Group. This is a monotonous, undifferentiated interval which was dated by Deegan and Scull (1977) as Middle Miocene to Recent. The youngest sediment, dated using calcareous nannofossils in the study material, was from the NS1 zone which was thought to be Pliocene in age. The assemblages of this age recovered from the North Sea Basin were rather poor and could only be dated by the occurrence of Helicosphaera sellii. The sub-divisions of the Pliocene onshore are based on Italian sequences and these prove to be difficult to recognise in NW Europe (Pomerol, 1982) due to their sub-tropical character. The foraminifera used to divide the Pliocene; Globorotalia margaritae and Globigerinoides obliquus extremus amongst others, do not extend to the North Sea Basin (G.K. Gillmore, pers. comm.). Very few marine Neogene sequences are found onshore in the British Isles. Most occur in south-east England nearest to the subsiding southern North Sea Basin , but even these are limited in stratigraphical and geographical extent. The Coralline Crag of East Anglia can be correlated with the shelly sands of the Brittany Peninsula and the Scaldisian beds of Belgium, but its relationship with the Pliocene sediment of the North Sea Basin is less clear due to the unrefined dating of this interval.

The Late Miocene (NS2) of the North Sea Basin also falls in part of the extensive Nordland Group, and appears to lie conformably below the NS1 zone. However, the calcareous nannofossil assemblages from this section are rather poor and only provide a vague age determination based on the FDO of Reticulofenestra pseudoumbilicus. Glauconitic, shelly sands (Tortonian/Messinian) were deposited in Denmark, northern Germany and Belgium, but the sea did not reach the British coast. In Belgium the Late Miocene is represented by the Deurnian sands. The foraminifera used to separate the Middle from the Late Miocene in the standard European stages: Neogloboquadrina acostaensis and Globorotalia menardii, are absent from the North Sea Basin where Uvigerina macrocarinata was used as an alternative (G.K. Gillmore, pers. comm.).

### 6.1.2 Hordaland Group ; North Sea Group - North Sea Clay Formation :

In well number 29/10-1 a good Middle Miocene assemblage, below the less well defined Late Miocene assemblage, was recovered and is assumed to have come from the Hordaland Group. In the Norwegian sector of the North Sea Basin a sandy interval, the Utsira Formation, is recognised in the Late to Middle Miocene of the Nordland Group, however, this is not found in the British sector from which the study material was collected. Zones NS3 and NS4 were well defined in well number 29/10-1, where they appeared below a line of unconformity (4800') which may mark the boundary between the Hordaland and Nordland Groups. The Langhian and Serravallian 'standard' stages are once again divided by a foraminiferal event (Praeorbulina FOD) which is not seen in the North Sea Basin. The FDO of Sigmomorphina regularis was used to separate the Middle and Early Miocene in the study material (G.K. Gillmore, pers. comm.). The FDO of the calcareous nannofossil species Discoaster exilis and Sphenolithus heteromorphus can be used to correlate this top part of the Hordaland Group with the Langhian.

The extensive Hordaland Group is also largely undifferentiated and composed of a monotonous series of marine shales. Deegan and Scull (1977) assign an age of Middle Eocene to Middle Miocene to this interval, thus it covered a wide time range. In the southern North Sea Basin, the same age of sediment was classed as the North Sea Clay Formation (in part) within the North Sea Group (Rhys, 1974). For such a large interval of time (approximately 33 million years) to be represented by a single formation is unheard of for the onshore Tertiary and reflects deposition in the centre of a rapidly subsiding basin. The zones NS5 - 7 were seen to occur conformably below NS3 and NS4 in well number 29/10-1, and comprise the youngest assemblages of other wells. In terms of calcareous nannofossil assemblages some of the most interesting levels within the Hordaland

Group are those which were dated as NS5 to NS7 zones (equivalent to NN4 - NN1 zones of Martini, 1971). These consistently yielded assemblages of good diversity, abundance, and preservation, and could be used to accurately date the sediment via a series of FDO's. A particularly interesting feature of these assemblages was the high numerical occurrence of *Braarudosphaera* and *Micrantholithus* species which are known to indicate shallow water (nearshore) marine conditions.

Bjorslev Nielsen *et al.*, (1986, fig.3., p.278) implied that sediment of an Early Miocene age was absent from the Central Graben (removed by the 'Savian' orogenic event), however, the results from this investigation show clearly that this is not the case.

The Early Miocene of the North Sea Basin is one of the best defined intervals in terms of calcareous nannofossil assemblages, but one of the most monotonous with respect to lithostratigraphy. Equivalent aged assemblages do not occur in onshore England, but have been recorded from the Belgian Basin and from the Rhone valley, France. In addition, the *Globigerina* Silts of the English Channel have been dated as NN2 and NN4-5 zones of Martini (1971) by Martini (1974) and correlated with the Aquitanian, Burdigalian and Langhian Stages (Curry *et al*, 1978). These are directly correlatable with the Early Miocene Houthalen sands (Houthalenian) and the early Middle Antwerp sands (Anversian) of the Belgian Basin. Martini (1988) also reported the occurrence of his NN2 and NN3 zones (= NS7 and NS6) from the Saint-Restitut, La Lauze and Montbrison sections in France.

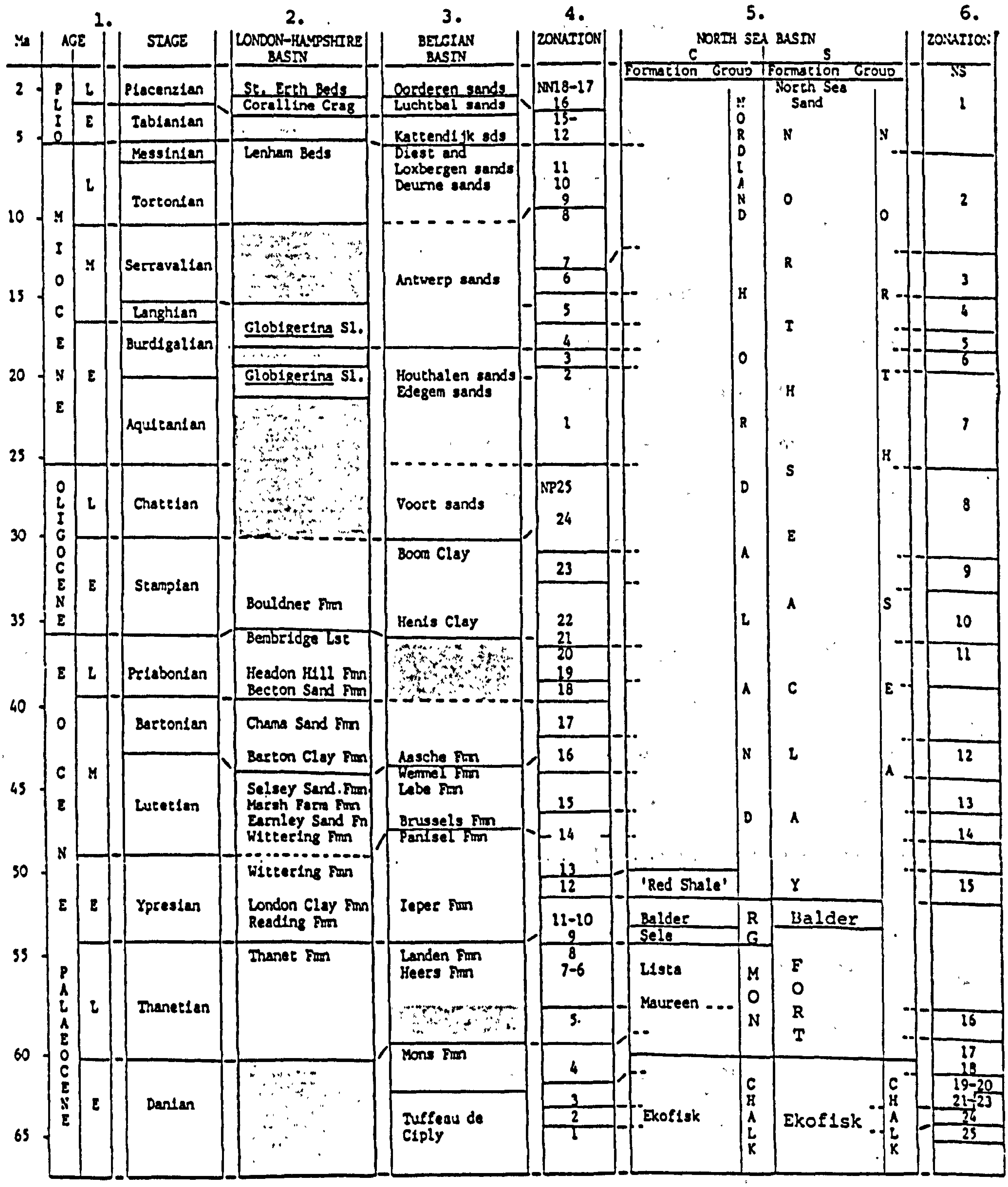
Late Oligocene assemblages (NS8) were often found directly below Miocene assemblages in the North Sea Basin study material, although the exact boundary was usually difficult to identify. The NS8 zone was widely distributed over the central North Sea Basin. The Chattian Stage which would correlate with sediment of this age is not present in Great Britain, but occurs in the German and Belgian Basins. The type section in the Rhine valley has been found by Roth (1970) to contain calcareous nannofossils of middle Oligocene age, however, Müller (1974) dated the poorly preserved assemblage as NP24/25 zone of Martini (1971), which would correlate them exactly with the NS8 assemblages of the central North Sea Basin, and those from the Rockall Basin (DSDP, Leg 12-117-2-3) studied here.

The Early Oligocene, in contrast to the Late Oligocene, was very poorly represented in the North Sea Basin study material; which may have partly been a result of the sampling pattern. In wells number 29/10-1 and 21/11-1 a poorly defined interval between the LDO of <u>Cyclicargolithus abisectus</u> and the FDO of <u>Reticulofenestra reticulata</u> (containing the FDO of <u>Reticulofenestra umbilicus</u>) defined zones NS9 and NS10. These are correlated with the Early Oligocene assemblages recovered from the Hampshire Basin (type area for the Hamstead Formation). The base of the Hamstead beds is continental like the upper part of the Bembridge Beds which they overlie. The Oligocene transgression is represented by marls with oysters. These may be correlated with the Oyster marls of the lower Stampian of the Paris Basin, and with the upper part of the Belgian Tongrian (Pomerol, 1982) (see Fig.46).

Examination of a sample from the Bembridge Marls Member of the Bouldner Formation (Solent Group) on the Isle of Wight yielded a very poor assemblage of calcareous nannofossils, which could not be used to confirm an Early Oligocene age. Aubry (1986), however, recognised the NP22 and NP23 zones of Martini (1971) in the lower part of the Stampian s. str. (Sables de Fontainebleau) and tentatively placed the base of the Stampian in NP22 (= NS10).

FIG. 46.

CORRELATION OF NORTH-WEST EUROPEAN CHRONOSTRATIGRAPHY AND BIOSTRATIGRAPHY WITH NORTH SEA BASIN LITHOSTRATIGRAPHY AND BIOSTRATIGRAPHY




1. Haq et al (1987) and Cavalier and Pomerol (1986)
2. Curry et al (1978) and Jones (unpub.) and Murray et al (1987)
3. Curry et al (1978) and Jones (unpub.) and Pomerol (1982)
4. Martini (1971)
5. Deegan and Scull (1977)
6. This study

The re-appearance of workable calcareous nannofossil assemblages in the central North Sea Basin correlates with the first appearance of calcareous nannofossil assemblages in the southern North Sea Basin (North Sea Clay Formation), and is indicative of Late Eocene age sections. Zone NS11 was found in wells number 49/9-1, 49/10-1, 21/11-1 and 14/29-1 and was well defined with respect to calcareous nannofossils, and could be accurately correlated with zones NP19/20 of Martini (1971). The Priabonian (type area = Posagno section, near Priabona in N. Italy) has preference over the Ludian as the upper Eocene reference stage in north-west Europe as it is more marine. The Priabonian as originally defined included part of zone NP18, NP19, NP20 and part of zone NP21. In these terms only the upper part of the stage is present in the North Sea Basin study material as zones NP17/18 were consistently absent. In material studied from the Hampshire Basin there was a marked lack of distinctive calcareous nannofossil assemblages of this age (Headon Hill Formation, barren).

The Middle Eocene Bartonian Stage has been the subject of many recent studies (Aubry, 1983,1985; Cavalier and Pomerol, 1986; etc.) that have enabled it to be better defined. The correspondence of the base of the Bartonian stratotype with the late Auversian of the Paris Basin was confirmed by Aubry (1986, p.300) who placed the stage within the nannofossil zones NP16 and NP17. The English Bartonian constitutes a good standard stage for the later part of the Middle Eocene in terms of nannofossils and other fossil groups (Cavalier and Pomerol, 1986) (see Fig.46. for correlation with other European formations). The southern North Sea Basin yielded excellent assemblages of NP16 age, which are herein correlated with the lower part of the Bartonian. Assemblages from the Hampshire Basin (Alum Bay) also confirmed the assignment of the Bartonian to the equivalent of Martini's (1971) NP16 (upper part) and NP17 zones. The Barton

Clay Formation yielded a good assemblage of calcareous nannofossils including the FOD of Reticulofenestra reticulata, which enabled the sample to be dated as equivalent to Martini's NP16/17 zone and correlated with the NS12 zone (in part) as defined herein (see Chapter 5).

In the southern North Sea Basin the NS12 zone is conformably underlain by the NS13 zone, which is also well defined in terms of its calcareous nannofossil assemblage. NS13 is correlated with the NP15 zone of Martini (1971). Aubry (1986, p.285) correlated the Lutetian Stage with the NP14, NP15 and lower part of NP16 zones of Martini (1971). As the NS12, NS13 and NS14 zones are readily identifiable in the study well material it is considered that the equivalent of the Lutetian Stage is fully represented in the southern North Sea Basin. The Lutetian is one of the best defined stages of the Palaeogene, as its top and base can be accurately determined in terms of planktonic zones. The present study would suggest that the Lutetian sensu-stricto can be applied to offshore sections. The Lutetian / Bartonian boundary is set at the LDO of R. reticulata, a datum which was found in both onshore and well sections (see Fig.46. for correlation with other European sections).

A hiatus exists in the North Sea Basin representing the time interval equivalent to the base of the NP14 zone and the NP13 zone (Early Eocene). This hiatus correlates with the top of the Ypresian Stage and the base of the undifferentiated clays of the Hordaland Group in the North Sea Basin. Throughout the London and Hampshire Basins also there is a barren interval at this level. In the Belgian Basin the Vlierzele Formation with the Aalterbrugge Lignitic horizon at its top and the Pittem Clay member at its base, as well as the Merelbeke member, have been dated using calcareous nannofossils by Steurbaut (1988) as NP13 and basal NP14 (Units IX, X, XI of Steurbaut, 1988) However, none of the nannofossil events used by Steurbaut (1988) were identified in this study in either the North Sea Basin or the London-Hampshire Basin.

In contrast, the "Red Shale" interval at the very base of the Hordaland Group, lying directly above the Balder Formation, yielded a relatively good assemblage of calcareous nannofossils (NS15 zone) in wells number 49/9-1, 49/10-1 and 29/7-1. These assemblages could be used to accurately date the interval as equivalent to Martini's (1971) NP12 zone on the basis of the occurrence of Discoaster lodoensis, in association with Tribrachiatus orthostylus, Discoaster kuepperi and Toweius occultatus. Investigation of the London Clay Formation from both the London and Hampshire Basins revealed a number of barren horizons, but also produced assemblages equivalent in age to those recovered from the North Sea Basin, as well as some which could be dated as slightly older (NP11 zone of Martini, 1971) on the basis of the absence of Discoaster lodoensis. It is clear that the upper part of the London Clay Formation (beds D and E of King, 1981) can be correlated with the "Red Shales" of the North Sea Basin, and that they both can be referred to the middle part of the Ypresian Stage.

The "Red Shales" of the North Sea Basin are also known to contain Globigerina gr. linaperta (NSP5 zone of King, 1983) and can be correlated with the Rønsnaes Clay of Denmark which has a similar microfossil content. Steurbaut (1988) reported a contemporaneous assemblage of calcareous nannofossils from the Roubaix Clay Member of the Belgian Basin, and was able to sub-divide it using successive nannofossil events. In the Paris Basin sediment of this age was referred to the 'Cuisian' Stage (e.g. Sables de Laon, and Sables de Cuise) by Aubry (1983, p.141). Sequence 10 of Stewart (1987) appears to correspond to this interval. He recognised a red-stained planktonic foraminiferal assemblage at its base and postulated a normal marine environment (confirmed by the presence of the calcareous nannofossil assemblage). The dominance of benthic arenaceous foraminifera above this short interval, and the absence of calcareous nannofossils, indicated that normal marine conditions were of short duration.

### 6.1.3 Rogaland Group - Balder Formation and Sele Formation :

The lowest part of the Ypresian, correlated with calcareous nannofossil zones NP9 and NP10 of Martini (1971) is not calcareous nannofossil bearing in the North Sea Basin study material nor in the London-Hampshire Basin study material. This interval is correlated with the top of the Rogaland Group in the North Sea Basin and corresponds to the Balder and Sele Formations in the central North Sea Basin and the Thulean Formation Formation in the southern North Sea Basin. The top of the Rogaland Group is marked by the change from the irregularly bedded shales of the Hordaland Group to the finely laminated tuffaceous shales of the Balder Formation (Deegan and Scull, 1977). The Balder Formation is generally separated from the underlying Sele Formation by the upward change in the wireline logs from higher to lower gamma ray response and lower to higher sonic velocity readings, probably corresponding to the sharp increase in the tuffaceous component of the Balder Formation (Deegan and Scull, 1977).

In the North Sea Basin, and adjacent sub-basins, calcareous nannofossils are absent, or sparsely distributed in Late Palaeocene and earliest Eocene sediments, and they were found to be absent over the Palaeocene/Eocene boundary interval. Consequently it has not been possible to relate these sequences directly to the established calcareous nannofossil zonation schemes. Knox (1984) suggested that indirect correlation was possible by tracing the volcanic ash layers of the North Sea Basin into the nannoplankton-bearing sequences of the north-east Atlantic. His conclusions were that the Palaeocene/Eocene boundary (NP9/NP10) corresponded to the base of the Sele Formation. Stewart (1987) recognised his sequence 9 as being of earliest Ypresian age and correlated it to the Balder and Sele Formations of the North Sea Basin. The only useful microfossil to be found within this part of the sequence is the diatom Coscinodiscus sp.1, which can be used to recognise the earliest Eocene in the North Sea Basin. The Balder Formation is generally correlated with the Mo Clay of Denmark and equivalent beds in the London Clay Formation of England and the Ieper Formation of Belgium.

### 6.1.4 Montrose Group - Lista Formation :

The central North Sea Basin equivalent to the top of the Thanetian Stage is the Lista Formation. This consists of non-laminated shales with minor limestone interbeds lying beneath the tuffaceous, laminated beds of the Sele Formation. In the study material this section was completely barren of calcareous nannofossils and contained only a sparse assemblage of agglutinated foraminifera (G.K. Gillmore, pers. comm.). A similar microfossil recovery was apparent from the southern North Sea Basin equivalent of the Lista Formation: the lower part of the North Sea Clay Formation. This can be correlated with sequence 7 and 8 of Stewart (1987) in the North Sea Basin, and approximately correlated with the Reading and Woolwich Formations (barren) of the London and Hampshire Basins at its top, and the Thanetian Formation of the London Basin, which does contain calcareous nannofossils, below.

The presence of zone NP8 in the Thanet Beds has long been recognised, but the assignment of the upper part to NP9 has been a matter of debate. Siesser et al. (1987) and work confirmed during this study has clarified the problem with an extensive re-examination of the type sections in Kent. The lowermost part of the Thanet beds were assigned to NP6/7; the rest of the formation, from the

Reculver Silts upwards, was assigned to zone NP8. The Woolwich (Reading) Bottom Bed at Clarendon Hill was assigned to zone NP9.

In the absence of calcareous nannofossils from the Lista Formation only indirect correlation with the Thanetian, using other microfossil groups was possible.

**6.1.5 Montrose Group - Maureen Formation (equivalent) :**

Underlying the Lista Formation in the study wells is the Maureen Formation (equivalent). This formation is very distinctive as it consists of large pebbles and clasts of Danian and Late Cretaceous age supported in a marl, shale and sandstone matrix. At its base in well number 30/6-2 an assemblage of calcareous nannofossils containing *Fasciculithus* species was recovered, dating the interval as NS16, equivalent to the NP5 zone of Martini (1971), and approximating to the basal part of the Thanetian Stage. In other wells studied this formation yielded assemblages equivalent to the NP4 zone of Martini (1971). It is just possible that these represented samples from blocks of Danian age, which had been reworked into the Maureen Formation, although it is also possible that they were *in situ* as the base of the Maureen Formation lies within this zone. As it contains assemblages of calcareous nannofossils of NP4/5 age, the Maureen Formation lies across the Thanetian/Danian Stage boundary. No beds of this age exist in England, but the Mons Formation (Montian) of Belgium and the Marnes de Meuden of the Paris Basin correlate with the base of the Maureen Formation (Jones, unpub.). Sequences 6 and 2 of Stewart (1987) correspond to the parts of the Maureen Formation recovered from the study material. In the southern Central Graben, Sequence 6 rests disconformabley on Sequence 2. Stewart (*op. cit.*, p.566) stated that Sequence 6 correlated with the upper part of the Undifferentiated Montrose Group (= Maureen Formation equivalent) and that *Spiroplectammina spectabilis* (form B) was abundant in this section, along with the re-occurrence of Spiroplectammina navaroanus and could be used to date the interval as NSB1b of King (1983), equivalent to middle Thanetian. This is in agreement with the data of Gillmore (pers. comm.). Such assemblages occurred in stratigraphically higher samples than the calcareous nannofossils mentioned above. Foraminiferal assemblages equivalent in age to the calcareous nannofossil assemblages could be found in Sequence 2 (B and C) type sediment (Stewart, 1987) near to the base of the Maureen Formation. In this interval the FDO of Cenodiscus lenticularis (radiolaria) followed by the FDO's of Globorotalia compressa and Clavulinoides anglicus / Clavulinoides parisiensis can be used to sub-divide the interval equivalent to the NP5 zone. The passage into the equivalent of the NP4 zone (= NSP1b/NSB1b) within the Maureen Formation is marked by the FDO's of the foraminifera Globorotalia trivialis and Globoconusa daubjergensis.

### 6.1.6 Chalk Group - Ekofisk Formation :

The lowest formation within the Tertiary of the North Sea Basin is the Ekofisk Formation (previously known as the Top Chalk Formation in the southern basin) which consists of a very distinctive chalk lithology (clearly demarcated on Completion Logs by lithological and wireline log responses). The calcareous nannofossils recovered from these formations provided excellent age assignments ranging from NS17 to NS23 (= NP4 to NP1 of Martini, 1971), although in most wells the age range of the Danian sediment was restricted to the NS17-18 zones.

Perch-Nielsen (1979) restricted the Danian in the type area to assemblages older than the NS17 zone, correlating the younger zones with the Selandian. However, as pointed out by Van Heck and Prins (1987, p.296) the intervals higher than NS17 in the North Sea Basin are usually barren of calcareous nannofossils, thus NS17 is included for convenience with the Danian as it occurs within the same formation. The Danian/Thanetian boundary in the North Sea Basin corresponds to the NP4/5 zonal boundary and is commonly found within the base of the Maureen Formation. The Ekofisk Formation is now known to include younger strata (NP4 zone) than previously thought in its upper part.

No sections of Danian age exist onshore in Great Britain, but the Calcaire Pisolitique of the Paris Basin, the Tuffeau de Ciply of the Belgian Basin, the Ommelanden Chalk Formation of the northern, sub-surface Netherlands, and the Danian Limestones of northern Germany, and the Danskekalk of Denmark and southern Sweden all contain intervals equivalent in age to those of the North Sea Basin (planktonic foraminifera and/or calcareous nannofossil age dating).

## 6.2 COMBINED CALCAREOUS NANNOFOSSIL AND FORAMINIFERAL BIOZONATION OF THE PALAEOGENE OF THE CENTRAL AND SOUTHERN NORTH SEA BASIN :

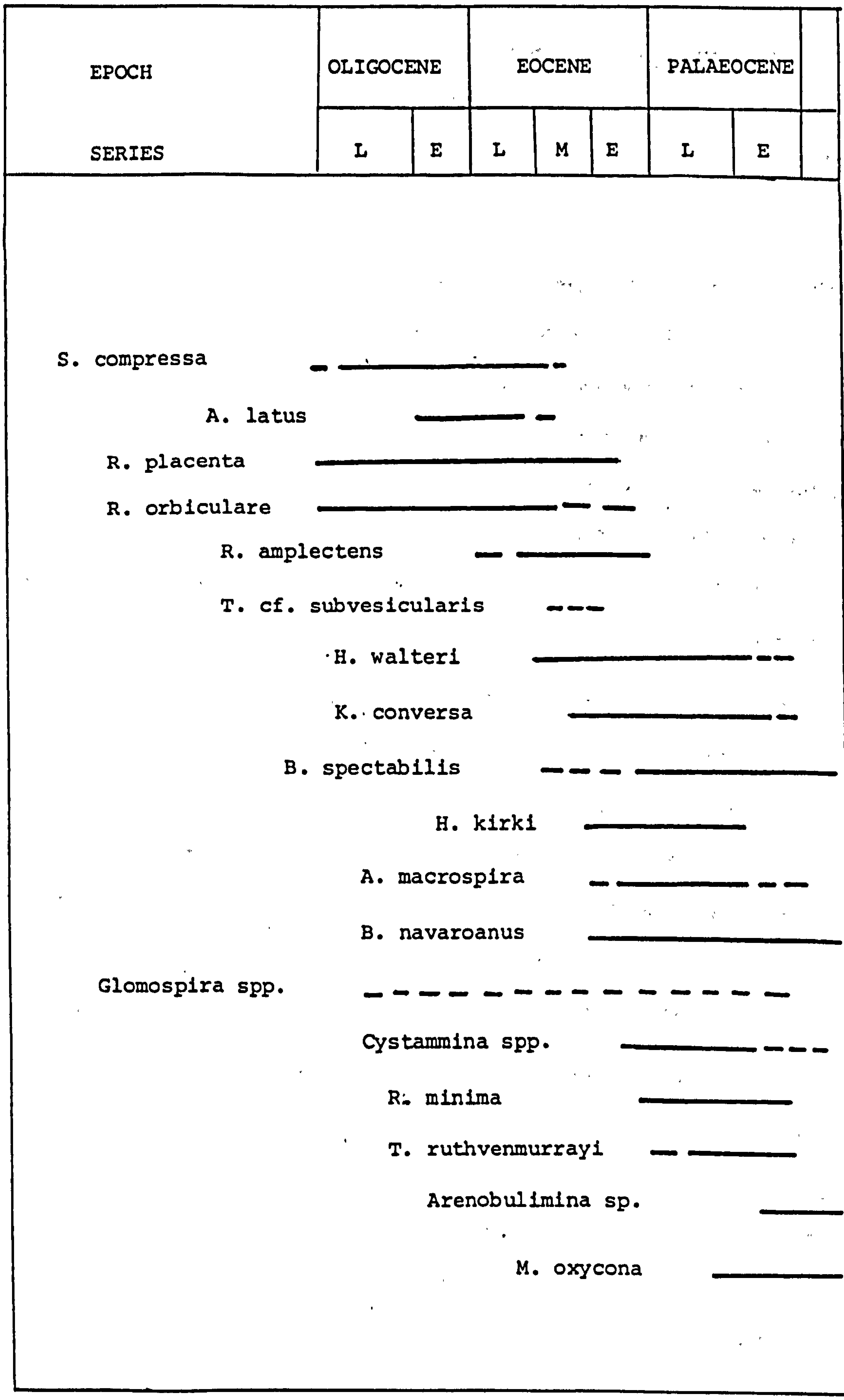
See Fig.49.

Work done by G.K. Gillmore (in parallel with this study) on the distribution of foraminifera in the North Sea Basin has resulted in the proposal of a biozonation scheme for the Palaeogene (see Figs.47. and 48.). By correlating this scheme with the one created in Chapter 5 for calcareous nannofossils, a combined zonation was tentatively recognised allowing a much finer biostratigraphical sub-division of this part of the Tertiary than in previous, single group schemes (e.g. Martini, 1971; King, 1983) because more events are available for use from a wider range of environments.

Each zone is defined by the FDO or LDO of a foraminifera and/or calcareous nannofossil species. Detailed information regarding the assemblages are to be found in Chapter 5 for the calcareous nannofossils, and in the thesis of G.K. Gillmore for the foraminifera. The zones defined herein are preliminary and, therefore only general remarks are given; type levels are not quoted and formal names not assigned. It is anticipated that a more thorough treatment of this combined zonation may be given in a joint post-doctoral publication.

**Zone 1 :** This interval corresponds to the NS8 zone as defined in Chapter 5 and includes the first Palaeogene occurrences of Spirosigmoilinella compressa, Globigerina officinalis and Globigerina ampliapertura. The foraminiferal assemblage indicates a somewhat restricted marine environment, although there appears to be no adverse effect on the calcareous nannofossil assemblage.

FIG. 47.




Distribution of Palaeogene marker species (benthic foraminifera)

FORAMINIFERAL ZONATION OF THE PALAEOGENE. FIG. 48.

| King (1983) NSB | King (1983) NSP | Blow (69) | ZONES |
|---|---|---|---|
| 8/9 | 9/10 | 20 | Spirosigmoilinella compressa |
| 7 | 9 | 18-20 | Rotaliatina bulimoides |
| 6 | | 15-17 | Karreralina conversa |
| 5 | | 14 | Ammomarginulina macrospira |
| 5 | | 11-12 | Bolivinopsis spectabilis form A |
| 5 | | 10-11 | Cenosphaera |
| 4 | | 8a-9 | Bolivinopsis navaroanus |
| 4 | | 8a | Globigerina gr. linaperta |
| 3 | | 7 | Coscinodiscus sp. 1 |
| 2/3 | | 6 | Sparse Interval |
| 2 | | 4-5 | Bolivinopsis spectabilis form B |
| 1b | 2 | 3 | Cenodiscus lenticularis |
| 1b | | 3 | Clavulinoides anglicus |
| 1a | | 1-2 | Danian Planktonics |

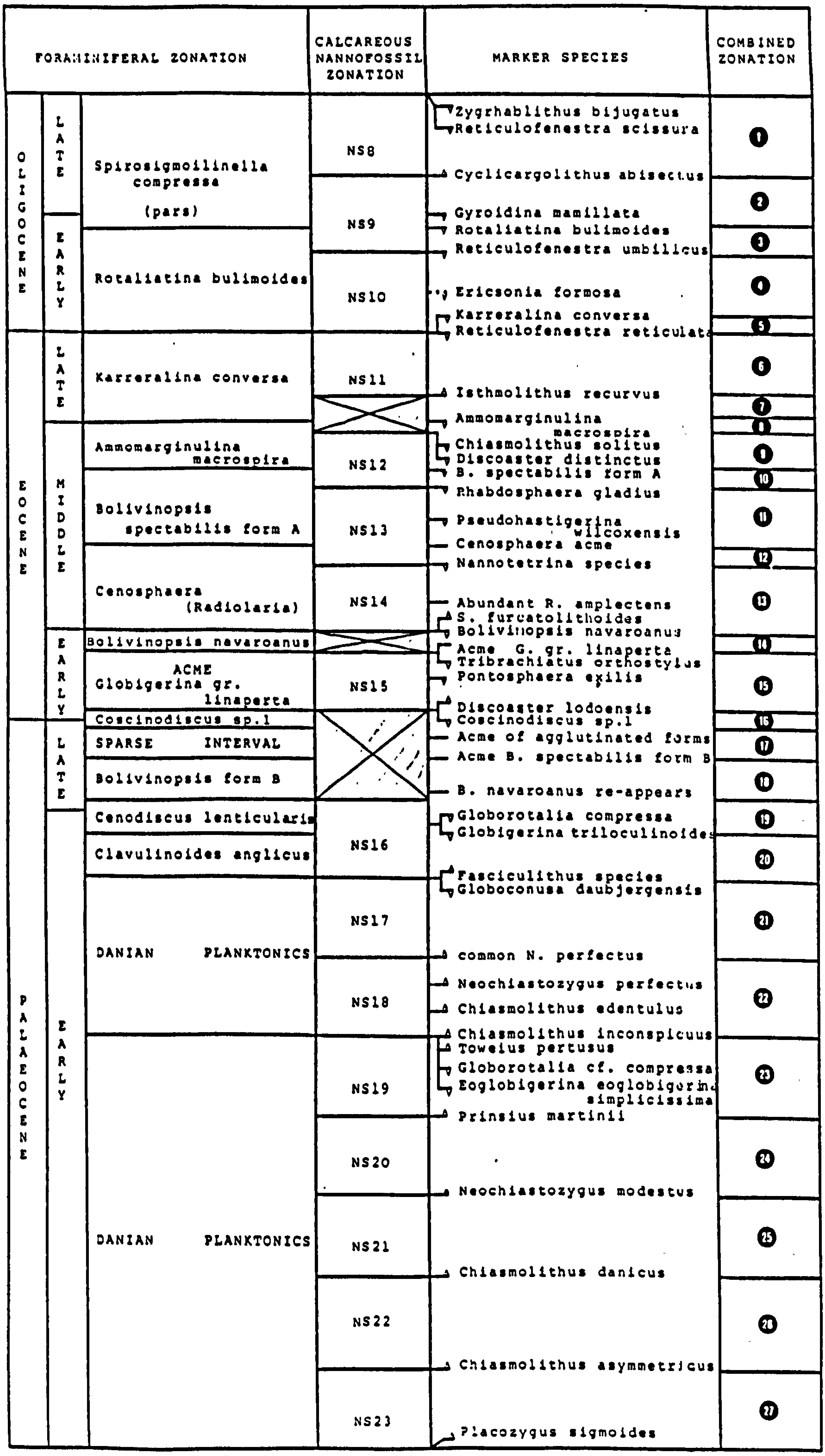
MARKER SPECIES

* S. compressa
* G. mamillata
* R. bulimoides
+ M. communis
* K. conversa, B. cookei, G. gr. linaperta
* A. macrospira, K. grzylowski
* B. spectabilis form A
* P. wilcoxensis
large numbers of Cenosphaera
Abundant R. amplectens
* B. navaroanus, A. pentacamerata
Common G. gr. linaperta
* T. brevispira
* Coscinodiscus sp. 1, Triceratum
Acme of B. spectabilis form B
Re-occurrence of B. navaroanus
* Cenodiscus
* G. compressa
* C. anglicus, G. beccariformis
* G. trivialis, G. daubjergensis
* G. simplicissima, G. aff. trivialis

* = FDO + = LDO

FIG. 49.

COMBINED CALCAREOUS NANNOFOSSIL AND FORAMINIFERAL ZONATION



**Zone 2** : This zone lies between the LDO of Cyclicargolithus abisectus and the FDO of Rotaliatina bulimoides. The lower part of the Spirosigmoilinella compressa Zone and the upper part of the NS9 zone are contained within this combined zone.

**Zone 3** : The lower part of NS9, down to the FDO of Reticulofenestra umbilicus, constitutes this zone in association with the upper part of the Rotaliatina bulimoides Zone. The foraminiferal assemblage indicates a normal marine environment, but the calcareous nannofossil assemblage was poor and could not be used to confirm this.

**Zone 4** : Foraminiferal and sedimentological evidence within this interval suggests high sea stand conditions (transgressive) in an outer shelf/upper slope environment. The FDO of Karreralina conversa marks the base of this zone and the FDO of Ericsonia formosa, if observed, could be used to sub-divide it.

**Zone 5** : A narrow interval between the FDO's of Reticulofenestra reticulata and Karreralina conversa in the upper part of the Late Eocene.

**Zone 6** : This zone contains the upper part of the Karreralina conversa Zone and the whole of NS11. Throughout the southern North Sea Basin and in parts of the central North Sea Basin the NS11 zone contained a well-preserved and diverse calcareous nannofossil assemblage despite the palaeoecological evidence of the foraminiferal assemblage indicating a reducing environment and unstable substrate conditions.

**Zone 7** : A barren interval (hiatus ?) in terms of calcareous nannofossils in the wells studied, but represented by the lower part of the Karreralina conversa Zone in the foraminiferal assemblage down to the FDO of Ammomarginulina macrospira.

**Zone 8** : Another thin zone lacking calcareous nannofossils, but containingforaminifera of the upper part of the Ammomarginulina macrospira Zone (including Karreralina grzybowskii).

**Zone 9** : Contains the FDO of Chiasmolithus solitus and Discoaster distinctus (the top of the NS12 zone), and the first calcareous nannofossil assemblages below the barren interval. The base of this zone is marked by the FDO of Bolivinopsis spectabilis form A.

**Zone 10** : This interval represents the lower part of NS12 and the upper part of the Bolivinopsis spectabilis form A Zone. It is a narrow zone of 'restricted' conditions according to the foraminiferal data, but containing a diverse and distinctive calcareous nannofossil assemblage in the southern part of the basin.

**Zone 11** : Lying between the FDO of Rhabdosphaera gladius and the Cenosphaera (Radiolaria) acme, this section corresponds to the lower part of the Bolivinopsis spectabilis form A Zone. The FDO of Pseudohastigerina wilcoxensis was recorded within this zone.

**Zone 12** : The association of large numbers of Cenosphaera above the LDO of Nannotetrina species makes this potentially an easily recognisable zone. The environmental conditions indicated by the abundance of this actinommid radiolaria genus are of a relatively open marine environment.

**Zone 13** : There is a reduction in the diversity of the calcareous nannofossil assemblage in this zone (equivalent to NS14). Abundant Rhabdammina amplectens indicates a water depth of between 200-700m.

**Zone 14** : The time interval corresponding to the top of the Early Eocene was barren of calcareous nannofossils, but contained the Bolivinopsis navaroanus Zone;

the species B. navaroanus has been described as occurring in restricted marine conditions (regressive), hence the absence of calcareous nannofossils.

**Zone 15** : This zone corresponds to the NS15 zone and represents the only occurrence of calcareous nannofossil assemblages in the North Sea Basin between the early Middle Eocene and the Early Palaeocene. The FDO of Pontosphaera exilis may be used to sub-divide this interval (see Steurbaut, 1988, p.101). The Globigerina gr. linaperta Acme Zone corresponds to this zone, thus there is a distinctive microfossil assemblage at this level including calcareous red-stained planktonics, calcareous benthonics and agglutinated forms (see discussion of 'Red Shales' in the Hordaland Group in Chapter 6). An open marine environment is indicated by the foraminiferal assemblage and borne out by the diversity of the calcareous nannofossil assemblage.

**Zone 16** : A very thin zone which can be recognised by the distinctive wireline log responses given by the Balder/Sele Formation, the total absence of calcareous nannofossils, and the FDO of the diatom species Coscinodiscus sp.1 (indicative of reducing conditions).

**Zone 17** : A sparse interval in terms of foraminifera, only poorly preserved agglutinated forms found, and totally barren of calcareous nannofossils.

**Zone 18** : Again there is an absence of calcareous nannofossils in this Late Palaeocene section, but the foraminiferal assemblage improves to include the acme of Bolivinopsis spectabilis form B and the re-appearance of Bolivinopsis navaroanus.

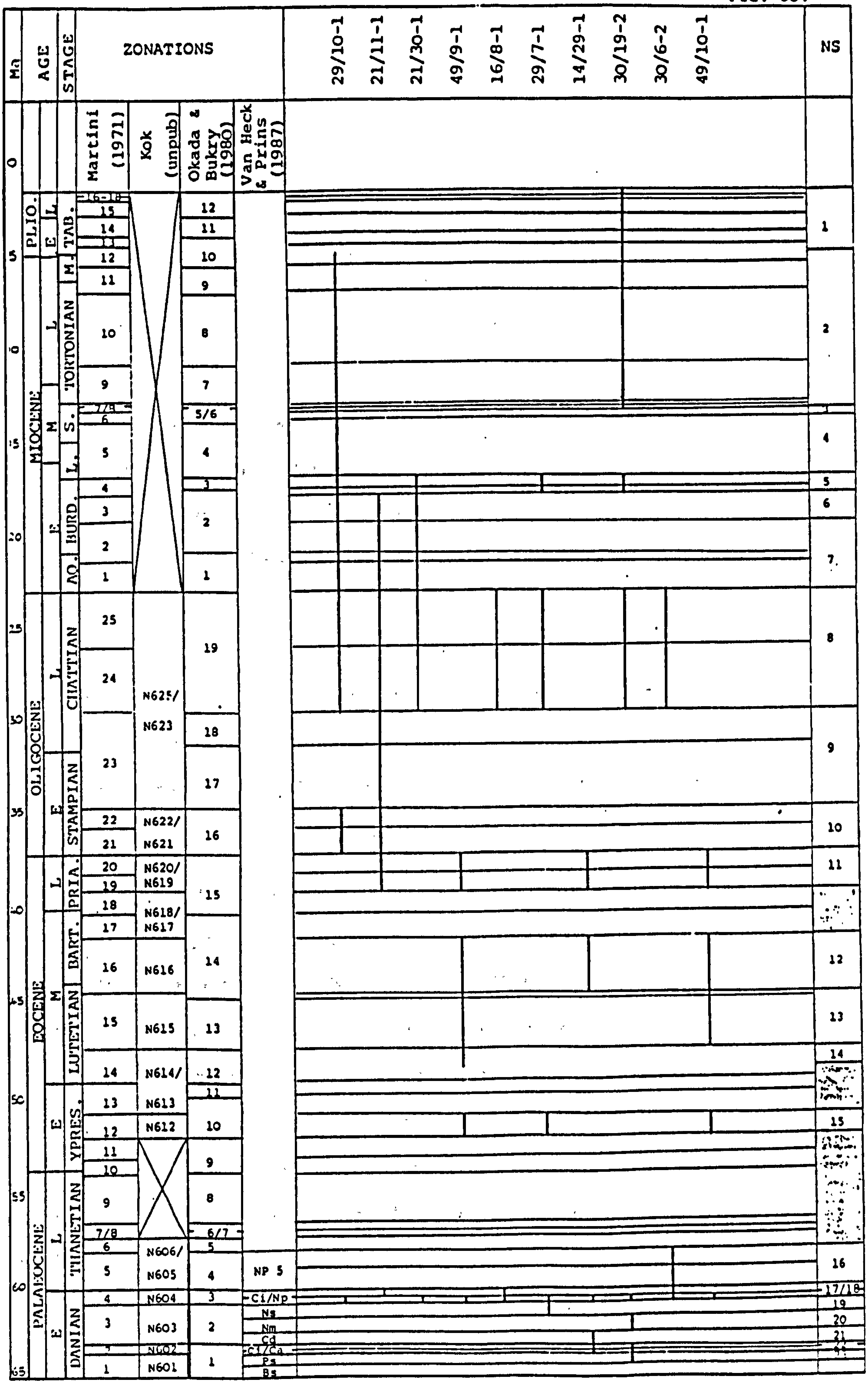
**Zone 19** : The FDO of the spongodiscid radiolaria Cenodiscus lenticularis marks the top of this zone, in which Globorotalia compressa and Globigerina *triloculinoides* have their FDO's. This zone is correlated with the 2c unit of Stewart (1987) (high sea stand conditions).

**Zone 20** : The basal Late Palaeocene (basal Thanetian) is seen to include the FDO's of *Clavulinoides anglicus*, *Clavulinoides parisiensis*, and *Gavelinella beccariiformis*. It also contains the FDO of *Fasciculithus* species; the first downhole occurrence of calcareous nannofossils in the Palaeocene.

**Zones 21 & 22** : The FDO of *Globoconusa daubjergensis* marks the top of zone 21, otherwise these zones correspond exactly to the NS17 and NS18 zones respectively.

**Zones 23 - 27** : The top of zone 23 is marked by the FDO's of *Globorotalia* cf. *compressa* and *Eoglobigerina eoglobigerina simplicissima*, otherwise all zones correspond to NS19-23 within the Ekofisk Formation (or equivalent).

FIG. 50.




Zonal coverage in the study wells.

## 7.1 CONCLUSIONS

The 'conclusions' to be drawn from a project such as this can best be described as a discussion of the results, the problems encountered, and ideas for future and further research into the subject.

**Sampling and preparation** : Although all the objectives of the study were met, many of them were necessarily provisional or only tentatively proposed because the complexity of the North Sea Basin is such that it cannot be fully analysed with just 12 wells (cf. King, 1983 = >200 wells, Van Heck and Prins, 1987 = 29 wells, Stewart, 1987 = 300 wells). However, within the time constraints of the project this represented a large number of samples (739) and covered both the central and southern basins, in shelf and deeper basin locations, and subsequently proved to cover the great majority of time intervals which are known to exist in the North Sea Basin. A greater number of wells concentrating on specific levels would be a good idea for future studies.

The material taken from individual wells was also restricted in that time would not allow too fine a sampling interval (not always necessary in any case) and the distribution of SWS's was not ideal for the study of calcareous nannofossils (as they are often concentrated around sand bodies). Hence many DC samples were included to cover large intervals. The problems of caving and contamination inherent in DC samples did not prove too great, and as long as the potential for such aberrant results was kept in mind, a reasonable biostratigraphy could be determined. Although many SWS's were analysed a lot of them proved to be barren and analysis of DC's was necessary to maintain the refinement of the biostratigraphy. Most of the comparative material was from outcrop sections or DSDP cores and could be treated in the same manner as SWS's (i.e. accurate position in the section, contaminant free, and both FOD's and LOD's could be used). In the case of the London Clay Formation from the north-central London area, the position of each sample was not always accurately known, but the monotonous nature of the sediment, the near horizontal bedding, and samples consisting of a single piece of clay, meant that contamination was minimalised. If further research were to concentrate on particular targets then there is little doubt that a number of wells containing sufficient SWS's, or even core coverage, could be made available, if not by an oil company then certainly by the BGS.

The method of preparation of a sample for calcareous nannofossil analysis is very much dependent on the operator's needs; in industry the more rapid methods are needed, whereas in academic research more time is available and a variety of methods employed (e.g. Smear, Centrifuge, etc.). During the course of this study a variety of techniques were tried and tested (see Tables 4-6) and a method for viewing the same specimen in light and scanning electron microscopes was developed. It is not claimed that this method is radically new, standard materials and equipment are used and other workers have developed methods to achieve a similar result, but what it does do is provide a methodology by which 'same specimen' analysis can be used during a routine preparation of samples, thus providing the maximum amount of information for that sample, and not as a complex ancillary study.

**Recovery and interpretation of study material** : The stratigraphical extent of the sediment recovered from the well material ranged from the Pliocene down to the Early Palaeocene in the central part of the basin and from the Late Eocene down to the Early Palaeocene in the southern part of the basin. The uppermost part of many central basin wells contained poorly consolidated sediment with very few SWS's. These yielded very poor assemblages of calcareous nannofossils which were broadly dated on the occurrence of just one or two species (plus foraminiferal evidence when available) as Pliocene to Late/Middle Miocene, and could only be divided into two very broadly defined zones (NS1-2). More intensive sampling in other wells may improve the biostratigraphy, but in the study wells the sandy nature of the sediment meant that further refinement is unlikely. The Middle and Early Miocene and the Late Oligocene parts of the section were consistently well defined in terms of calcareous nannofossil zones, but the Early Oligocene was difficult to determine due to caving in DC samples and the barren nature of SWS's. It is likely that intensive SWS coverage in a series of wells which contain sediment of this age will conclusively prove the existence of this interval, and may even refine the biostratigraphy using the FDO's of Ericsonia formosa and Lanternithus minutus. Late Oligocene assemblages from the South Atlantic Ocean and the Hatton-Rockall Basin (DSDP Sites 329 and 117 respectively) were very similar (although better preserved and slightly more diverse) to those recovered from the central North Sea Basin. Müller (1979) reported a wide geographic distribution for sediments of this age and to the reported occurrences in the Faeroe-Iceland Ridge, North Atlantic Ocean, and Hatton-Rockall Basin, the central North Sea Basin can now be added.

The Late Eocene sediment throughout the basin provided some of the most diverse assemblages of calcareous nannofossils, but also contained a hiatus in the study wells (equivalent to Martini's NP17-18 zones) which left a gap in the proposed biozonation. King (1983, p.19) points out that beds of this age are not easily recognisable in the North Sea Basin due to the absence or rarity of their index species. The Middle Eocene of the central basin was consistently barren, although it contained extremely diverse nannofloras in both the southern basin and in the Hampshire Basin (Isle of Wight). The southern basin assemblages in particular allowed a refined biostratigraphy and further study of southern North Sea Basin material (only 3 wells herein) is recommended for biostratigraphical and taxonomical purposes. Late Eocene assemblages from Alabama were significantly different from those of the well material in that the extinctions (LOD's) of both Discoaster saipanensis and Discoaster barbadiensis were well defined and could be used to delimit the Eocene/Oligocene boundary. The differences in the assemblages illustrate how latitude affects the geographical distribution of calcareous nannofossils, and the subsequent effect on biostratigraphical resolution. The Early Eocene of the North Sea basin is largely barren, this is explained in part (Stewart, 1987, p.574) by a major and sudden fall in sea level in the basin, accompanied by regional tilting and erosion (introduction of clastics). Just below this barren interval, in what are termed the 'Red shales', a very good assemblage of calcareous nannofossils was recovered equivalent in age to the London Clay Formation of the London and Hampshire basins, and correlatable with the Early Eocene (NP11-12) clays of Belgium (Steurbaut, 1988). This sequence represents the return to a more normal marine environment for the North Sea Basin after the low sea level stand conditions of the Balder formation and before the regression described above.

Nowhere in the North Sea Basin were assemblages of Late Palaeocene age (NP6-9) recovered (Foraminifera were also sparse, G.K. Gillmore, pers. comm.), although material from the Thanetian stratotype of Pegwell Bay, Kent yielded calcareous nannofossils equivalent in age to Martini's (1971) NP8 zone. It may be that the transgressive nature of the sea at this time led to a relative sea level rise, possibly restricting sediment input to the basin. If sediment supply was altered the amount of calcium carbonate in centre of the basin may fall and consequently the CCD would rise, hence preventing the preservation of calcareous nannofossils which are present in more peripheral localities above the level of the CCD. Alternatively increased sediment supply may have diluted the amount of plankton in the sediment, and/or a high percentage of organic matrerial may have 'soured' the environment.

Early Palaeocene assemblages were widespread and reasonably diverse and, although not well preserved, proved to be of great value in high resolution biostratigraphy for this part of the sequence.

**Biozonation** : The initial problem to be overcome in the establishment of a zonation scheme for the North Sea Basin was that of contamination. Due to the nature of the well study material there were a number of potential sources of aberrant data :

| | |
|---|---|
| Natural | a. Primary - reworking of material about lines of unconformity, etc. |
| | b. Secondary - re-sedimentation of already reworked material. |
| Man-made | a. Primary - mixing of assemblages in the drilling mud. |
| | b. Secondary - down-hole caving below casing points. |
| | c. Laboratory contamination. |

On the whole up-sequence reworking was readily identifiable, with major unconformities marked on the Completion Logs and only Cretaceous specimens present in younger strata with any regularity. On the other hand down-hole caving was prevalent in DC samples and LDO's could not be relied on stratigraphically. With these problems in mind the zonation was based primarily on the FDO's of species, supplemented by LDO's in SWS's and the general character of the assemblage. The zonation is numbered from younger to older strata as drilling proceeds in this direction, and divides the Tertiary of the North Sea Basin into 23 zones, three of which may be sub-divided.

The biozonation scheme (NS zones) is specific to the North Sea Basin (as were the schemes of Van Heck and Prins 1987, and Perch-Nielsen 1979), but contains events broadly recognisable in the north-west European area. At certain levels (e.g. Early Miocene) there is a close similarity with the 'standard' scheme of Martini (1971), but at other levels there is little correlation (e.g. Late Eocene). Some NS zones are not as refined as those of the 'standard' schemes (e.g. NS1-2) due to the constraints on sampling, the preservational state of the recovered assemblages, and most significantly to the high-latitude position of the basin. However, there are levels (e.g. NS17-23) where a greater refinement than the 'standard' scheme can be achieved by utilising successive evolutionary appearances in lineages.

The scheme established in this project is not complete in the sense that it contains some gaps. An increase in sampling (specifically SWS's) around particular levels (e.g. Late Eocene NP17-18) would probably clarify some of these intervals and zonal assignments could be adjusted accordingly. However, other gaps (e.g. Late Palaeocene/Early Eocene NP6-10) are consistent throughout the North Sea Basin and will not be resolved biostratigraphically using calcareous nannofossils. This does not have implications with respect to the biozonation scheme as long as it is applied to the North Sea Basin only. An advance for the study of Tertiary calcareous nannofossils in the North Sea Basin would be to extend this study into the more northern parts of the basin. Facies changes occur as one goes northwards (e.g. Danian chalk becomes marl) and there are opportunities to study the effect this has on the calcareous assemblages. An extremely well-preserved and diverse assemblage is known from the Late

Cretaceous marl in Block number 210; there may be an equivalent assemblage in the Danian marl above, which would have obvious biostratigraphical applications.

In the interests of obtaining as much biostratigraphical information as possible for a basin, studies nowadays are inter-disciplinary as a matter of routine. The study of Palaeogene foraminifera by G.K. Gillmore, conducted in parallel with this project, has provided valuable biostratigraphical information which both complements and supplements the calcareous nannofossil data. For instance the Late Palaeocene interval is covered by the Coscinodiscus sp.1 Zone and the Bolivinopsis form B Zone, where there was no calcareous nannofossil data, and the Middle and Late Eocene can be divided into 8 combined zones, where there were previously only 4 for each group. This increase in refinement (27 combined zones as opposed to 23 NS zones and 15 foraminiferal zones) is an advantage as the greater number of correlation levels allows a more complete picture of the geological history of the basin to be proposed (foraminifera can also be used to indicate bathymetry, palaeotemperature, etc.). In addition to the microfossil information, this project also utilised minor amounts of lithological data and wireline log characteristics to create the combined zonation scheme. Although no zones were actually defined by these characters the information they provided where microfossil data was poor (e.g. Balder and Sele Formations) was valuable in determining the stratigraphical position of samples.

This type of multi-disciplinary approach can be applied together with the 'sequence stratigraphy' approach of, amongst others, Stewart (1987) to provide a complete picture of the development of a basin. Stewart (op. cit.) utilised the 'depositional sequence' ideas of Vail et al. (1977) to sub-divide the Palaeogene of the North Sea Basin into 10 depositional sequences. These sequences are calibrated by foraminiferal and palynological data. The Danian to Early Ypresian is divided into ten foraminiferal zones and seven palynological zones; calcareous nannofossils were not used. If the results of the present study are correlated with those of Stewart (1987, p.562) then a much more refined micropalaeontological calibration of the sequences can be obtained, particularly in the Danian. Calcareous nannofossils have tended to be ignored in the past when seismic stratigraphy, biostratigraphy and sequence stratigraphy have been brought together. It has been demonstrated herein that for major parts of the Palaeogene and Neogene of the North Sea Basin calcareous nannofossils are useful biostratigraphical markers and they should be included in joint studies with seismically defined sequences and other microfossil groups in order to obtain the most accurate interpretation of basin development.

**Systematic descriptions** - The vast majority of species observed in this study are well established in the literature and, therefore, required only minimal coverage in the taxonomic section; a brief synonymy list and notification of their occurrence was deemed sufficient. Groups which required greater investigation were dealt with in separate sub-chapters. *Cyclicargolithus floridanus* and *Cyclicargolithus abisectus* were analysed for similarity in structure. They are, for the time being retained as separate species (for biostratigraphical purposes), but it is envisaged that more sophisticated analysis methods (image analysis) would allow a much larger data base to be analysed with the probable conclusion that they are a single morphotype separated solely on size differences. The Family Noelaerhabdaceae presented a much more demanding problem, the *Reticulofenestra* group in particular required emendation and clarification. The introduction to this particular problem highlights how loosely the generic name has been applied in the past and how various authors have emphasised the significance of different morphological elements of the reticulofenestrid coccolith. The possession of a central area grill, in addition to the other properties peculiar to Reticulofenestra, is shown here to be essential for the assignment of this generic name, but variations in the geometry of the grill are of species level significance only (cf. Bown, 1987, p.12). A rigorous re-examination of the genus, including investigation of topotype material, resulted in emendation of generic diagnosis and description and detailed systematic descriptions of species considered valid. The evolution of the genus Reticulofenestra can be traced in the evolution of the Family Noelaerhabdaceae from its inception with small, simple Prinsius species, through Toweius where structural complexity reached a peak, to Reticulofenestra. This pattern of development and the nature of the coccolith structure is very similar to patterns observed in the Mesozoic e.g. Watznaueria (Bown, Burnett pers. comm.). Such an observation raises interesting questions about the possibilities of iterative evolution with an ancestral stock perhaps of Biscutum-like coccoliths.

The adoption of a morphological classification, viewed within an evolutionary framework is an attempt to recognise the true biological relationships within this group. The production of a compendium of Reticulofenestra species was designed to make comparisons between species easier. Standardisation of terminology and comments from the original descriptions is also seen as an aid to identification of a particular species.

**Postscript** - The proposal of a biozonation scheme for the whole of the Tertiary of the North Sea Basin is an advance on previous knowledge of the distribution of calcareous nannofossils in the North Sea Basin. It will undoubtedly be used as a stratigraphical tool, and can be independently applied despite the gaps within it. Good biostratigraphical control within the Neogene of this basin using calcareous nannofossils has been demonstrated to a considerable extent whilst the opportunities for further investigation with a view to geographical and stratigraphical extension of the scheme, as well as integration with other disciplines allied to the oil exploration industry, remain for future researchers.

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## 7.2 REFERENCES

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ADDENDUM :

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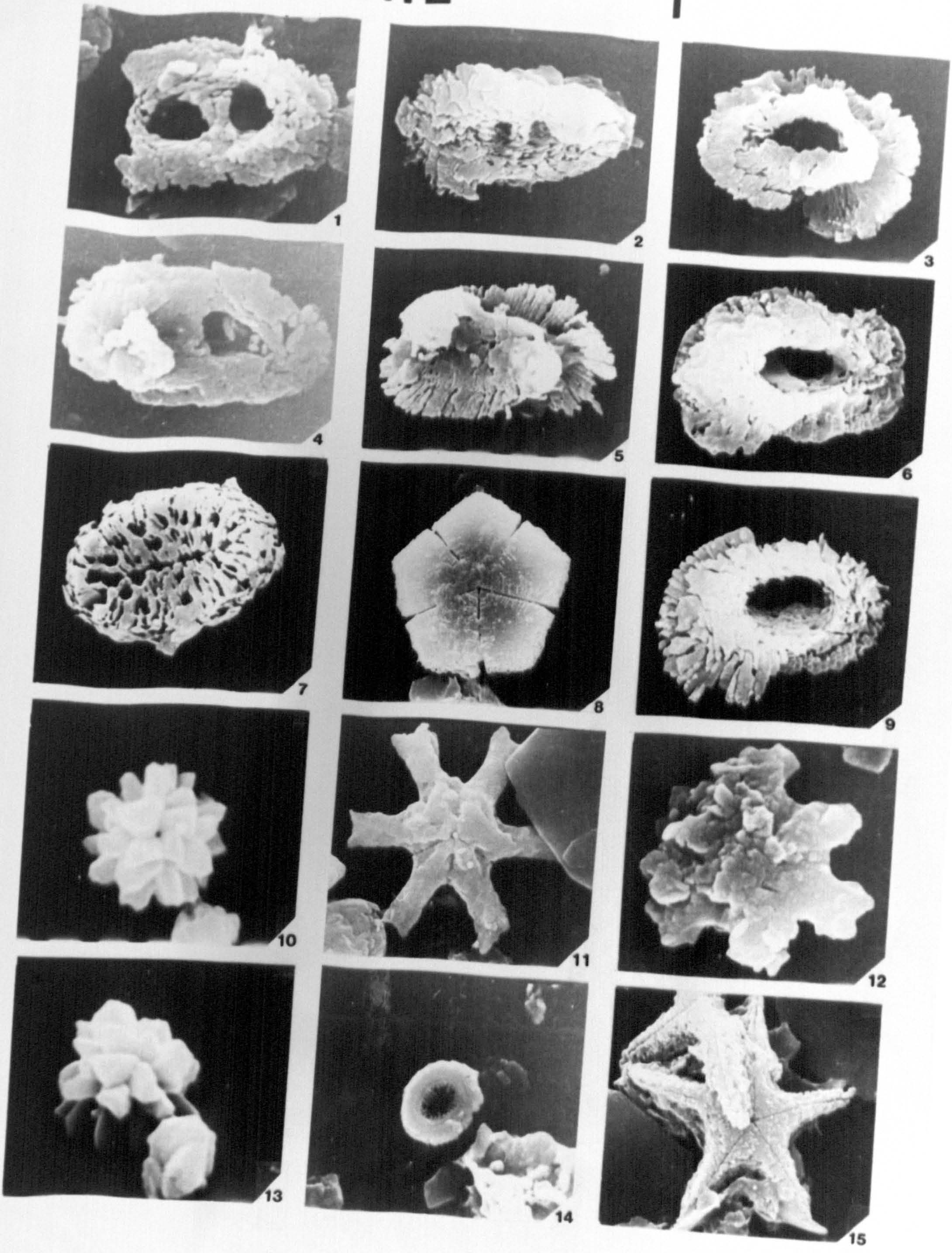
# PLATES

## PLATE 1 : SCANNING ELECTRON MICROGRAPHS

1,4. Helicosphaera mediterranea Muller : Fig.1 UCL-2335-08, distal view of a broken specimen; Fig.4 UCL-2335-10, distal view of an overgrown specimen. Shell/Esso North Sea well number 21/11-1, depth 2393'. Early Miocene. X5,000.
2,5. Helicosphaera carteri (Wallich) Kamptner : Fig.2 UCL-2216-17, distal view; Fig.5 UCL-2229-17, proximal view. Shell/Esso North Sea well number 29/10-1, depth 5796'. Early Miocene. X5,000.
3,6 & 9. Helicosphaera ampliaperta Bramlette and Wilcoxon : Fig.3 UCL-2216-21, proximal view; Fig.6 UCL-2229-09, distal view; Fig.9 UCL-2229-20, distal view of an etched specimen. Shell/Esso North Sea well number 29/10-1, depth 5796'. Early Miocene. X5,000.
7. Pontosphaera multipora (Kamptner) Roth : UCL-2229-11, proximal view. Shell/Esso North Sea well number 29/10-1, depth 5796'. Early Miocene. X5,000.
8. Braarudosphaera bigelowii (Gran and Braarud) Deflandre : UCL-2229-22, well preserved specimen. Shell/Esso North Sea well number 29/10-1, depth 5785'. Early Miocene. X2,500.
10,13. Sphenolithus moriformis (Bronniman and Stradner) Bramlette and Wilcoxon : Fig. 10 UCL-2371-11, top view; Fig.13 UCL-2371-10, side view of same specimen. DSDP 36-329-30-2 (147-148cm). Late Oligocene. X5,000.
11. Discoaster variablis Martini and Bramlette : UCL-2216-25, moderately preserved specimen. Shell/Esso North Sea well number 29/10-1, depth 5796'. Early Miocene. X5,000.
12. Discoaster deflandrei Bramlette and Riedel : UCL-2335-07, highly overgrown specimen. Shell/Esso North Sea well number 21/11-1, depth 2393'. Early Miocene. X5,000.
14. Reticulofenestra minuta Roth : UCL-2335-06, proximal view. Shell/Esso North Sea well number 21/11-1, depth 2393'. Early Miocene. X5,000.
15. Micrantholithus aequalis : UCL-2216-02, corroded specimen. Shell/Esso North Sea well number 29/10-1, depth 5785'. Early Miocene. X5,000.

# PLATE 1



## PLATE 2 : SCANNING ELECTRON MICROGRAPHS

1,2,3,8 & 10. Chiasmolithus altus Bukry and Percival : Fig.1 UCL-2371-16, distal view; Fig.2 UCL-2371-33, proximal view; Fig.3 UCL-2371-27, distal view; Fig.8 UCL-2371-35, proximal view; Fig.10 UCL-2371-15, proximal view. DSDP 36-329-30-2 (147-148cm). Late Oligocene. X3,725.

4,9, & 15. Cyclicargolithus abisectus (Müller) Wise : Fig.4 UCL-2309-20, distal view of a broken specimen; Fig.9 UCL-2309-19, distal view; Fig.15 UCL-2309-21, distal view of a well preserved specimen. JOIDES Hole 5, 554' 10" below top. Late Oligocene. X7,500.

5. Cyclicargolithus abisectus (Müller) Wise : UCL-2371-31, distal view. DSDP 36-329-30-2 (147-148cm). Late Oligocene. X2,500.

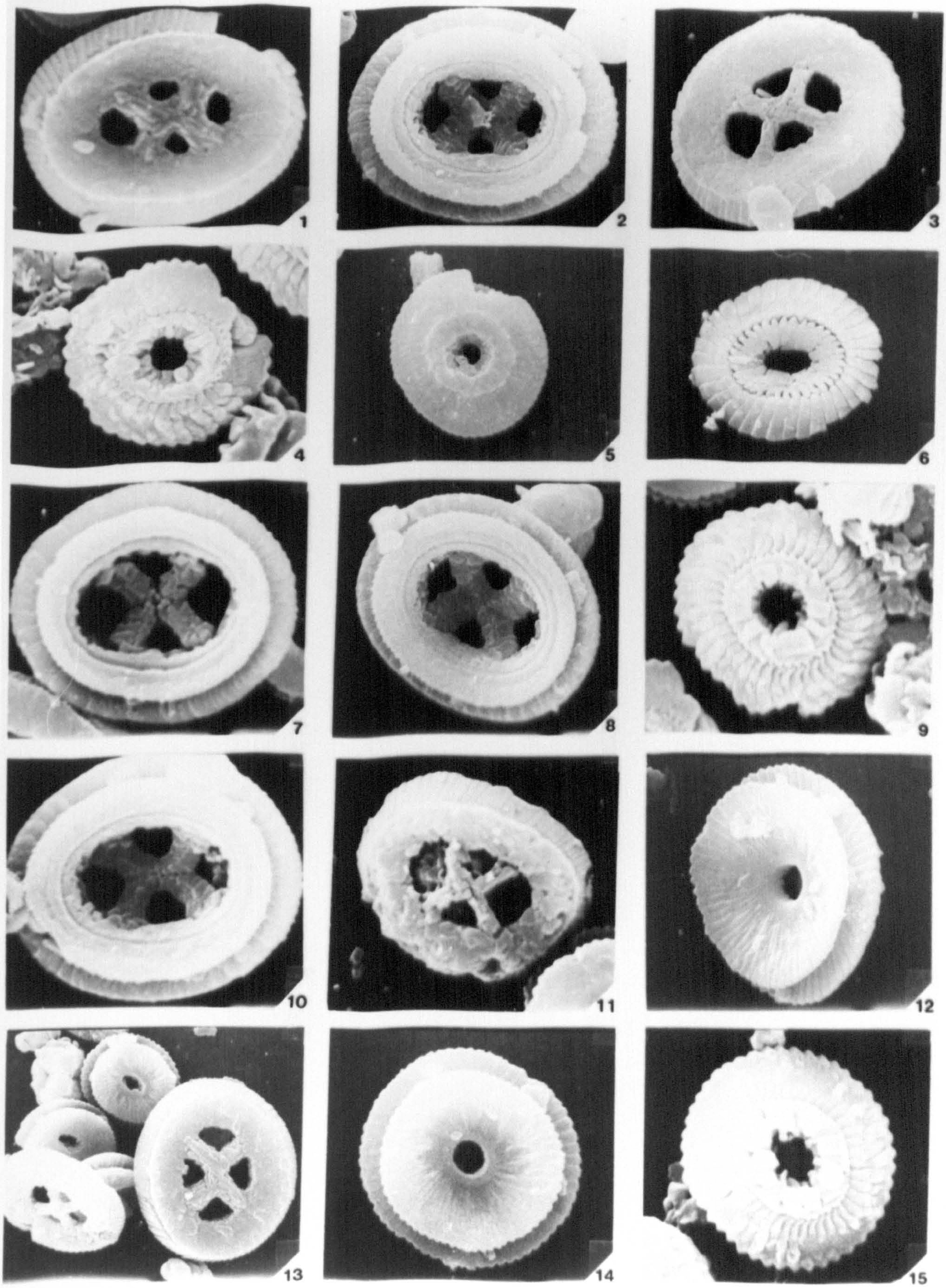
6. Coccolithus pelagicus (Wallich) Schiller : UCL-2216-10, distal view. Shell/Esso North Sea well number 29/10-1, depth 7122'. Late Oligocene. X5,000.

7 & 11. Chiasmolithus altus Bukry and Percival : Fig.7 UCL-2371-06, proximal view; Fig.11 UCL-2371-07, distal view. DSDP 36-329-29-2 (138-139cm). Late Oligocene. X3,725.

12 & 14. Cyclicargolithus abisectus (Müller) Wise : Fig.12 UCL-2371-28, oblique proximal view; Fig.14 UCL-2371-34, proximal view. DSDP 36-329-30-2 (147-148cm). Late Oligocene. X3,725.

13. Chiasmolithus altus Bukry and Percival : Fig.13 UCL-2371-32, distal view. DSDP 36-329-30-2 (147-148cm). Late Oligocene. X2,500.

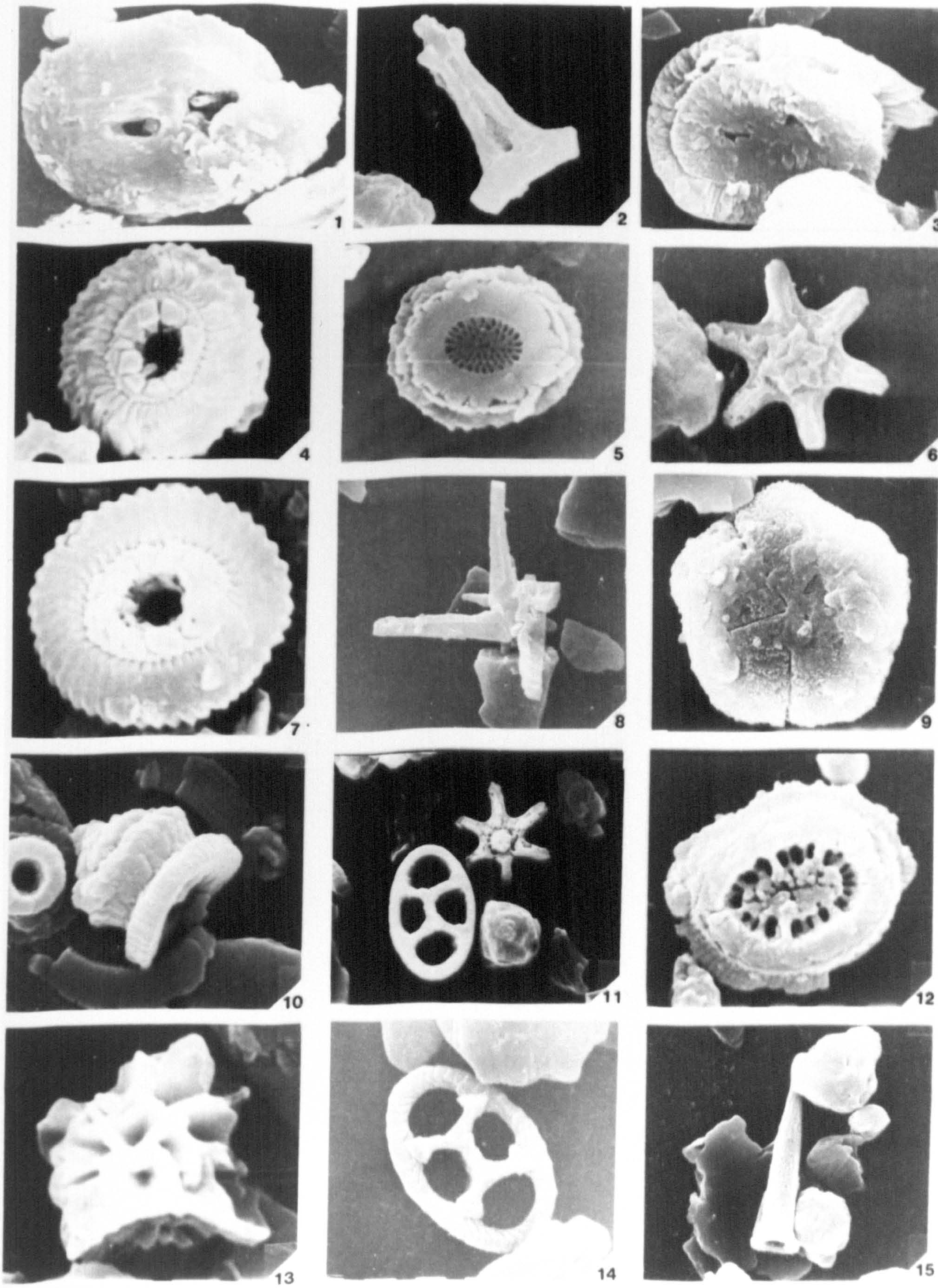
# PLATE 2



## PLATE 3 : SCANNING ELECTRON MICROGRAPHS

1. Helicosphaera recta Haq : UCL-2335-27, distal view. JOIDES Hole 5, 554' 10" below top. Early Oligocene. X5,000.
2. Zygrhablithus bijugatus (Deflandre) Deflandre : UCL-2601-25, side view. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene. X5,000.
3. Helicosphaera recta Haq : UCL-2309-18, proximal view. JOIDES Hole 5, 554' 10" below top. Early Oligocene. X5,000.
4. Cyclicargolithus floridanus (Roth) Bukry : UCL-2335-23, distal view. JOIDES Hole5, 554' 10" below top. Early Oligocene. X7,500.
5. Reticulofenestra scissura?Hay, Mohler and Wade : UCL-2335-14, proximal view. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene. X2,500.
6. Discoaster tanii Bramlette and Riedel : UCL-2650-17, slightly etched specimen. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X5,000.
7. Cyclicargolithus floridanus (Roth) Bukry : UCL-2335-29, distal view. JOIDES Hole 5, 554' 10" below top. Early Oligocene. X7,500.
8. Nannotetrina nitida (Martini) Aubry : UCL-2650-26, broken specimen. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X2,500.
9. Braarudosphaera bigelowii (Gran and Braarud) Deflandre : UCL-2216-01, slightly overgrown. Shell/Esso North Sea well number 29/10-1, depth 5785'. Early Miocene. X2,500.
10. Naninfula deflandrei Perch-Nielsen : UCL-2601-01, side view. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene. X7,500.
11. Neococcolithes dubius (Deflandre) Black and Discoaster tanii Bramlette and Riedel : UCL-2553-19. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. X2,500.
12. Reticulofenestra daviesii (Haq) Haq : UCL-2335-21, distal view. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene. X5,000.
13. Sphenolithus moriformis (Brönniman and Stradner) Bramlette and Sullivan : UCL-2335-25, side view of a well preserved specimen. JOIDES Hole 5, 544' 10" below top. Early Oligocene. X7,500.
14. Neococcolithes dubius (Deflandre) Black : UCL-2650-18, distal view. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X5,000.
15. Blackites spinosus (Deflandre and Fert) Hay and Towe : UCL-2423-14, side view. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X2,500.

# PLATE 3



## PLATE 4 : SCANNING ELECTRON MICROGRAPHS

1,2 & 3 Neococcolithes dubius (Deflandre) Black : Fig.1 UCL-2423-07, distal view; Fig.2 UCL-2423-10, oblique distal view of the central area; Fig.3 UCL-2423-08, distal view. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X5,000.

4. Chiasmolithus oamaruensis (Deflandre) Hay, Mohler and Wade : UCL-2578-03, proximal view, broken proximal rim. S136/898. William's Bluff, Oamaru, New Zealand. Late Eocene. X2,500.

5 & 6. Lanternithus minutus Stradner : Fig.5 UCL-2462-10, top view; Fig.6 UCL-2462-11, oblique side view. Shell/Esso North Sea well number 49/9-1, depth 1990'. Middle Eocene. X5,000.

7. Reticulofenestra umbilicus (Levin) Martini and Ritzkowski : UCL-2462-05, oblique proximal view. Shell/Esso North Sea well number, depth 1737'. Middle Eocene. X5,000.

8. Pemma angulatum Martini : UCL-2534-21, four detached segments. Shell/Esso North Sea well number 49/9-1, depth 1890'. Middle Eocene. X3,725.

9. Helicosphaera lophota Bramlette and Sullivan : UCL-2534-19, etched distal view. Shell/Esso North Sea well number 49/9-1, depth 1890'. Middle Eocene. X5,000.

10. Ericsonia formosa (Kamptner) Haq : UCL-2462-12, etched proximal view. Shell/Esso North Sea well number 49/9-1, depth 1990'. Middle Eocene. X3,725.

11. Reticulofenestra daviesii (Haq) Haq : UCL-2578-04, distal view. S136/898. William's Bluff, Oamaru, New Zealand. Late Eocene. X7,500.

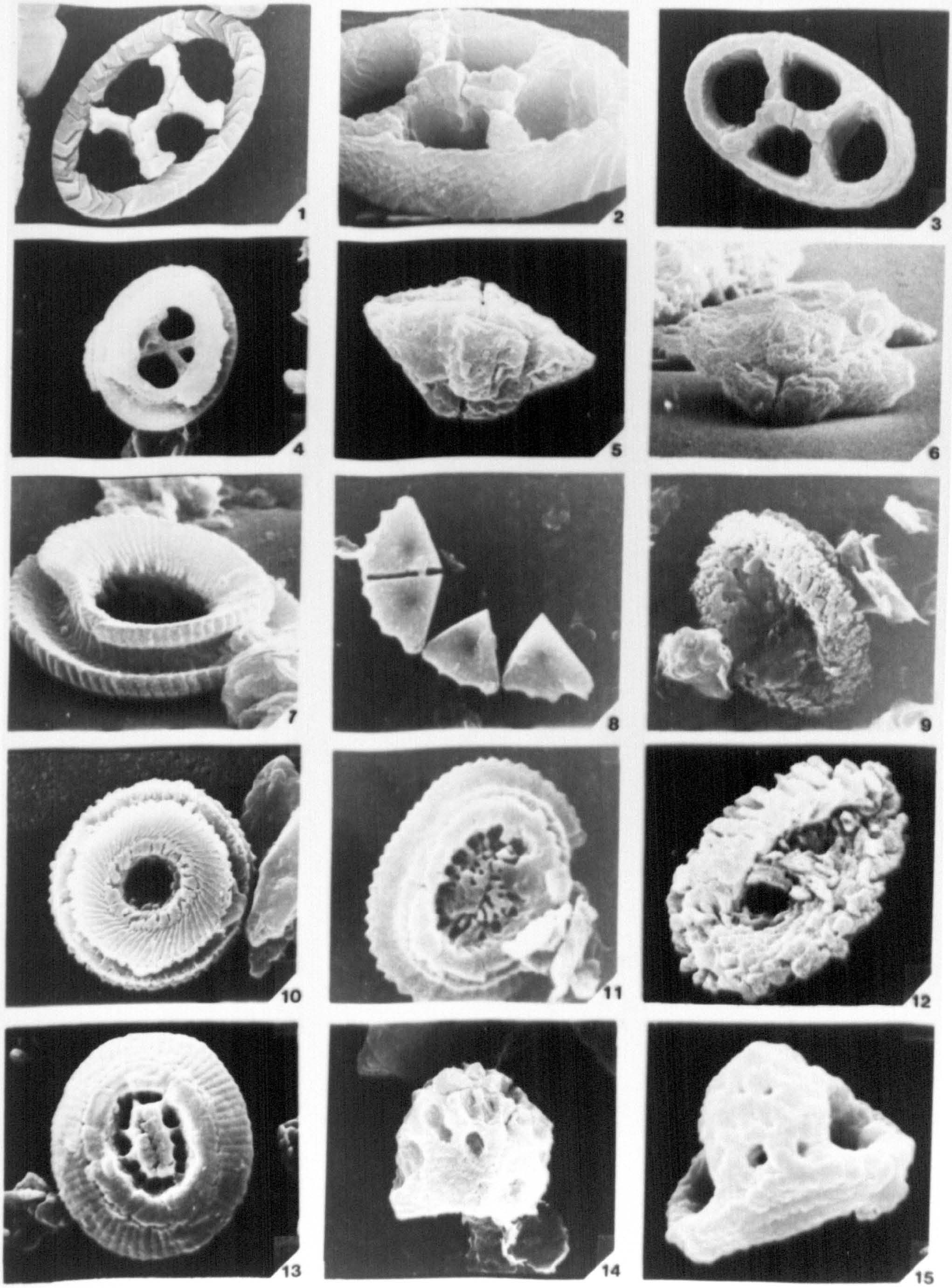
12. Helicosphaera seminulum Bramlette and Sullivan : UCL-2462-19, etched distal view. Shell/Esso North Sea well number 49/9-1, depth 1990'. Middle Eocene. X5,000.

13. Reticulofenestra callida (Perch-Nielsen) Bybell : UCL-2601-32, distal view. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene. X5,000.

14. Daktylethra punctulata Gartner : UCL-2462-07, side view. Shell/Esso North Sea well number 49/9-1, depth 1737'. Middle Eocene. X5,000.

15. Orthozygus aureus (Stradner) Bramlette and Wilcoxon : UCL-2601-33, oblique side view. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene. X7,500.

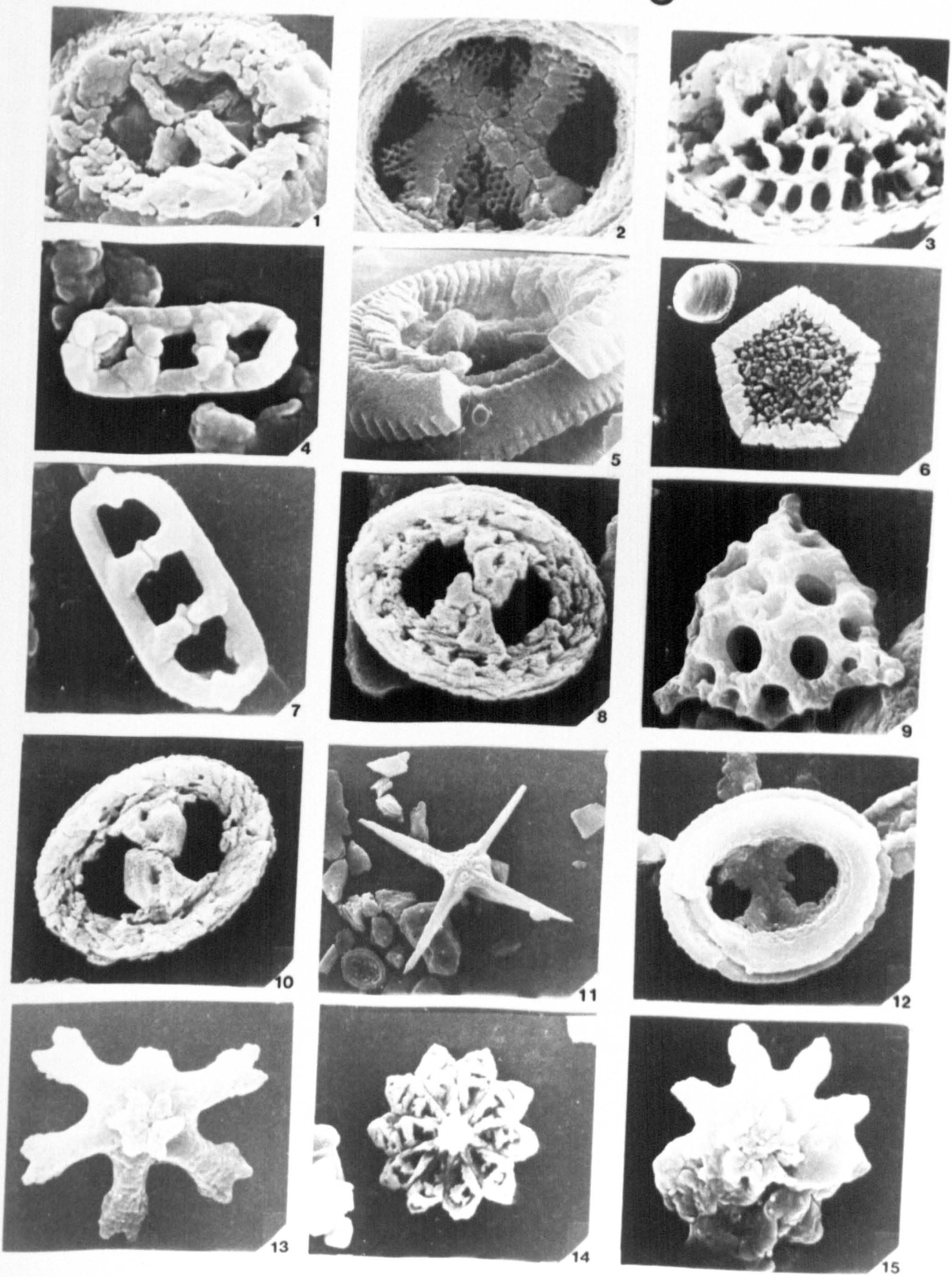
# PLATE 4



## PLATE 5 : SCANNING ELECTRON MICROGRAPHS

1. Chiasmolithus solitus (Bramlette and Sullivan) Locker : UCL-2346-06 distal view of central area cross structure. HB753. Hampden Beach, New Zealand. Middle Eocene. X5,000.
2. Chiasmolithus solitus (Bramlette and Sullivan) Locker : UCL-2423-12 central area detail, proximal view. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X7,500.
3. Pontosphaera multipora (Kamptner) Roth : UCL-2216-23 detail of central area grill, distal view. Shell/Esso North Sea well number 29/10-1, depth 5796'. Early Miocene. X7,500.
4,7. Isthmolithus recurvus Deflandre : Fig.4 UCL-2337-03 plan view, overgrown; Fig.7 UCL-2337-12 plan view. Shell/Esso North Sea well number 21/11-1, depth 3120'. Late Eocene. X5,000.
5. Reticulofenestra umbilicus (Levin) Martini and Ritzkowski : UCL-2423-18 oblique distal view of a broken specimen. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X7,500.
6. Goniolithus fluckigeri Deflandre : UCL-2423-14 distal view. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X5,000.
8 & 10. Transversopontis pulchra (Deflandre) Perch-Nielsen : Fig.8 UCL-2423-23 distal view; Fig.10 UCL-2423-22 distal view. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X7,500.
9. Lithostromation perdurum Deflandre : UCL-2423-21. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X5,000.
11. Nannotetrina fulgens (Stradner) Achutan and Stradner : UCL-2423-01 well preserved specimen. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X1,000.
12. Chiasmolithus oamaruensis (Deflandre) Hay, Mohler and Wade : UCL-2337-11 proximal view, overgrown central cross structure. Shell/Esso North Sea well number 21/11-1, depth 3120'. Late Eocene. X2,500.
13. Discoaster distinctus Bramlette and Riedel : UCL-2346-04 broken specimen. HB753. Hampden Beach, New Zealand. Middle Eocene. X5,000.
14. Discoaster elegans Bramlette and Sullivan : UCL-2553-23 slightly overgrown specimen. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X5,000.
15. Discoaster saipanensis Bramlette and Riedel : UCL-2346-05 overgrown specimen. HB753. Hampden Beach, New Zealand. Middle Eocene. X3,750.

# PLATE 5



## PLATE 6 : SCANNING ELECTRON MICROGRAPHS

1 & 3. Zygrhablithus bijugatus (Deflandre) Deflandre : Fig.1 UCL-2346-29 side view; Fig.3 UCL-2346-15 side view of an overgrown specimen. S136/898. William's Bluff, Oamaru, New Zealand. Early Oligocene. X5,000.

2. Zygrhablithus bijugatus (Deflandre) Deflandre : UCL-2216-08 side view. Shell/Esso North Sea well number 29/10-1, depth 7122'. Early Oligocene. X7,500.

4. Ericsonia subdisticha (Roth) Roth : UCL-2346-22 distal view of an overgrown specimen. S136/898. William's Bluff, Oamaru, New Zealand. Early Oligocene. X7,500.

5. Discoaster elegans Bramlette and Sullivan : UCL-2349-21. HB758. Hampden Beach, New Zealand. Middle Eocene. X5.000.

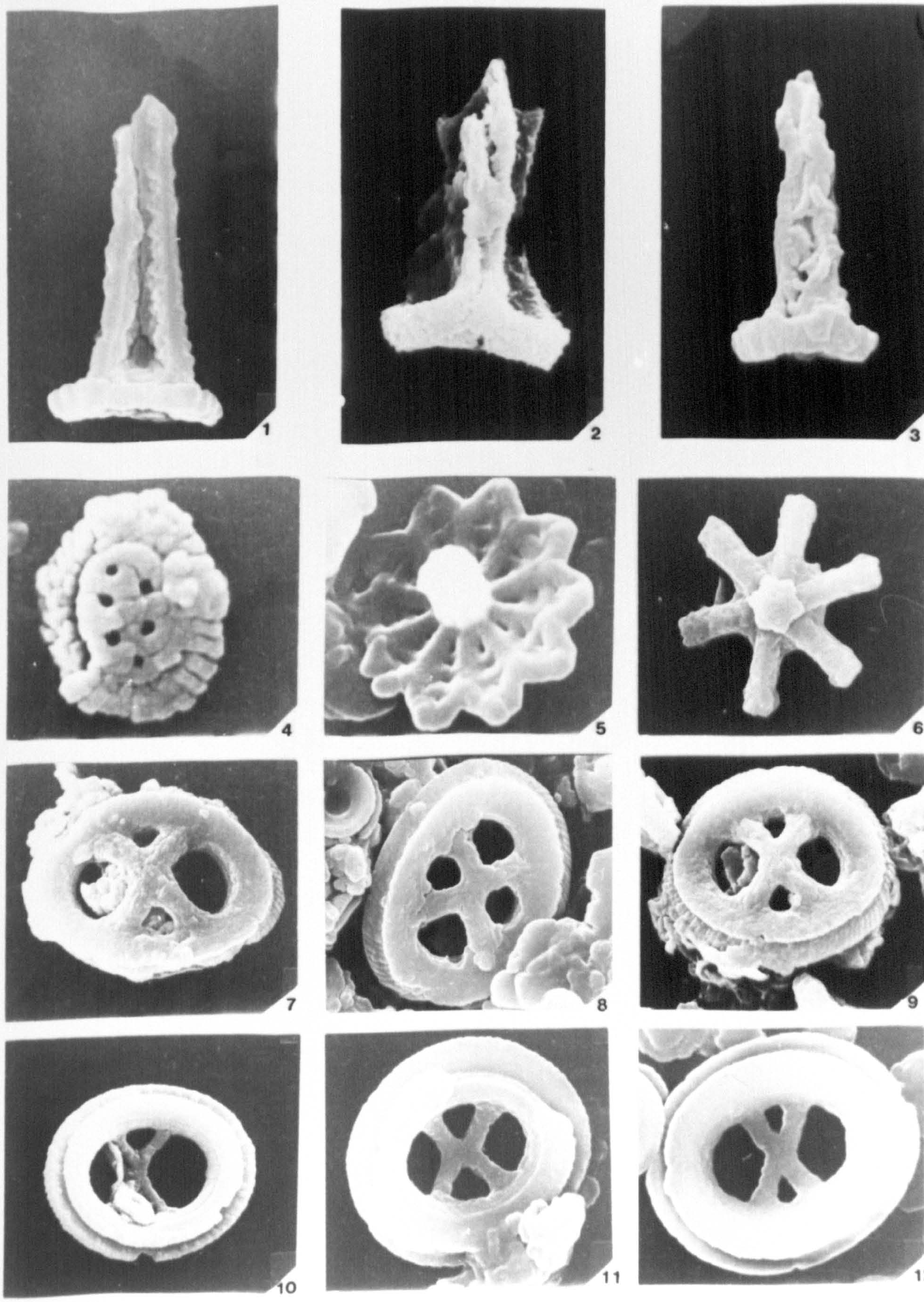
6. Discoaster tanii Bramlette and Riedel : UCL-2346-10. HB753. Hampden Beach, New Zealand. Middle Eocene. X3,750.

7,9 & 10. Chiasmolithus oamaruensis (Deflandre) Hay, Mohler and Wade : Fig.7 UCL-2346-32 distal view; Fig.9 UCL-2349-29 distal view; Fig.10 UCL-2346-21 proximal view of a well preserved specimen. S136/898. William's Bluff, Oamaru, New Zealand. Early Oligocene. X2,500.

8 & 11. Chiasmolithus expansus (Bramlette and Sullivan) Gartner : Fig.8 UCL-2349-25 distal view; Fig.11 UCL-2349-26 proximal view. HB768. Hampden Beach, New Zealand. Middle/Late Eocene. X2,500.

12. Chiasmolithus oamaruensis (Deflandre) Hay, Mohler and Wade : UCL-2349-23 proximal view. HB768. Hampden Beach, New Zealand. Middle/Late Eocene. X3,750.

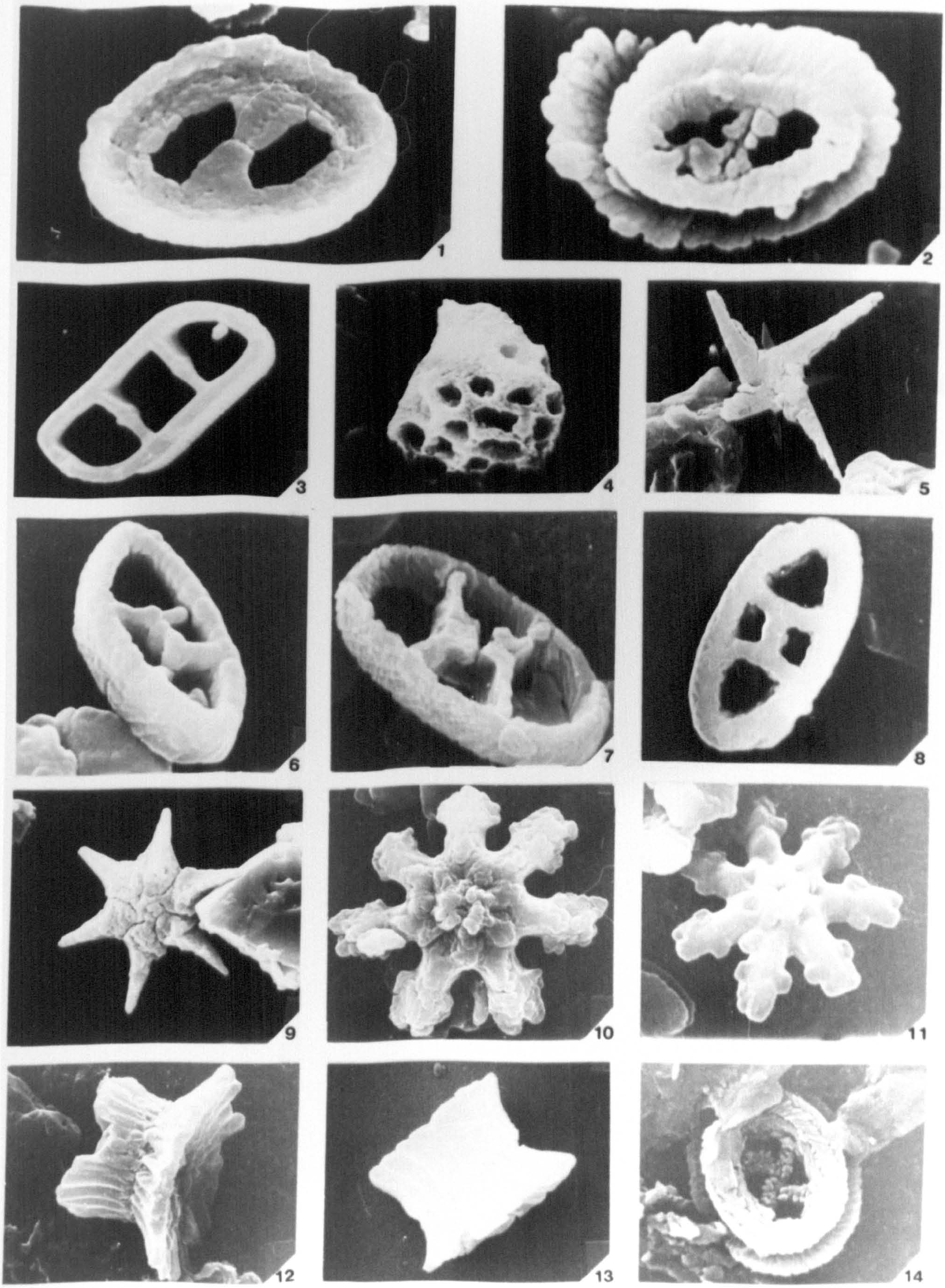
# PLATE 6



## PLATE 7 : SCANNING ELECTRON MICROGRAPHS

1. Transversopontis pulchra (Deflandre) Perch-Nielsen : UCL-2346-33. S136/898. William's Bluff, Oamaru, New Zealand. Early Oligocene. X5,000.
2. Helicosphaera euphratis Haq : UCL-2346-24 proximal view. S136/898. William's Bluff, Oamaru, New Zealand. Early Oligocene. X7,500.
3. Isthmolithus recurvus Deflandre : UCL-2349-34 plan view. S136/898. William's Bluff, Oamaru, New Zealand. Early Oligocene. X5,000.
4. Daktylethra punctulata Gartner : UCL-2566-09 side view. Shell/Esso North Sea well number 49/9-1, depth 1890'. Middle Eocene. X5,000.
5. Nannotetrina nitida (Martini) Aubry : UCL-2553-29 broken specimen. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X3,750.
6 & 8. Neococcolithes minutus (Perch-Nielsen) Perch-Nielsen : Fig.6 UCL-2349-10 oblique distal view; Fig.8 UCL-2349-04 proximal view. HB758. Hampden Beach, New Zealand. Middle Eocene. X5,000.
7. Neococcolithes dubius (Deflandre) Black : UCL-2650-19 oblique distal view. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene. X7,500.
9. Discoaster sublodoensis Bramlette and Sullivan : UCL-2346-34. HB728. Hampden Beach, New Zealand. Early Eocene. X2,500.
10 & 11. Discoaster binodosus Martini : Fig.10 UCL-2349-08 slightly overgrown specimen; Fig.11 UCL-2349-19 well preserved specimen. HB758. Hampden Beach, New Zealand. Middle Eocene. X2,500.
12 & 13. Heliolithus riedelii Bramlette and Sullivan : Fig.12 UCL-2433-03 oblique side view; Fig.13 UCL-2582-02 side view. AG16. Pegwell Bay, Kent. Late Palaeocene. X5,000.
14. Chiasmolithus edentulus Van Heck and Prins : UCL-2433-07 proximal view. AG16. Pegwell Bay, Kent. Late Palaeocene. X5,000.

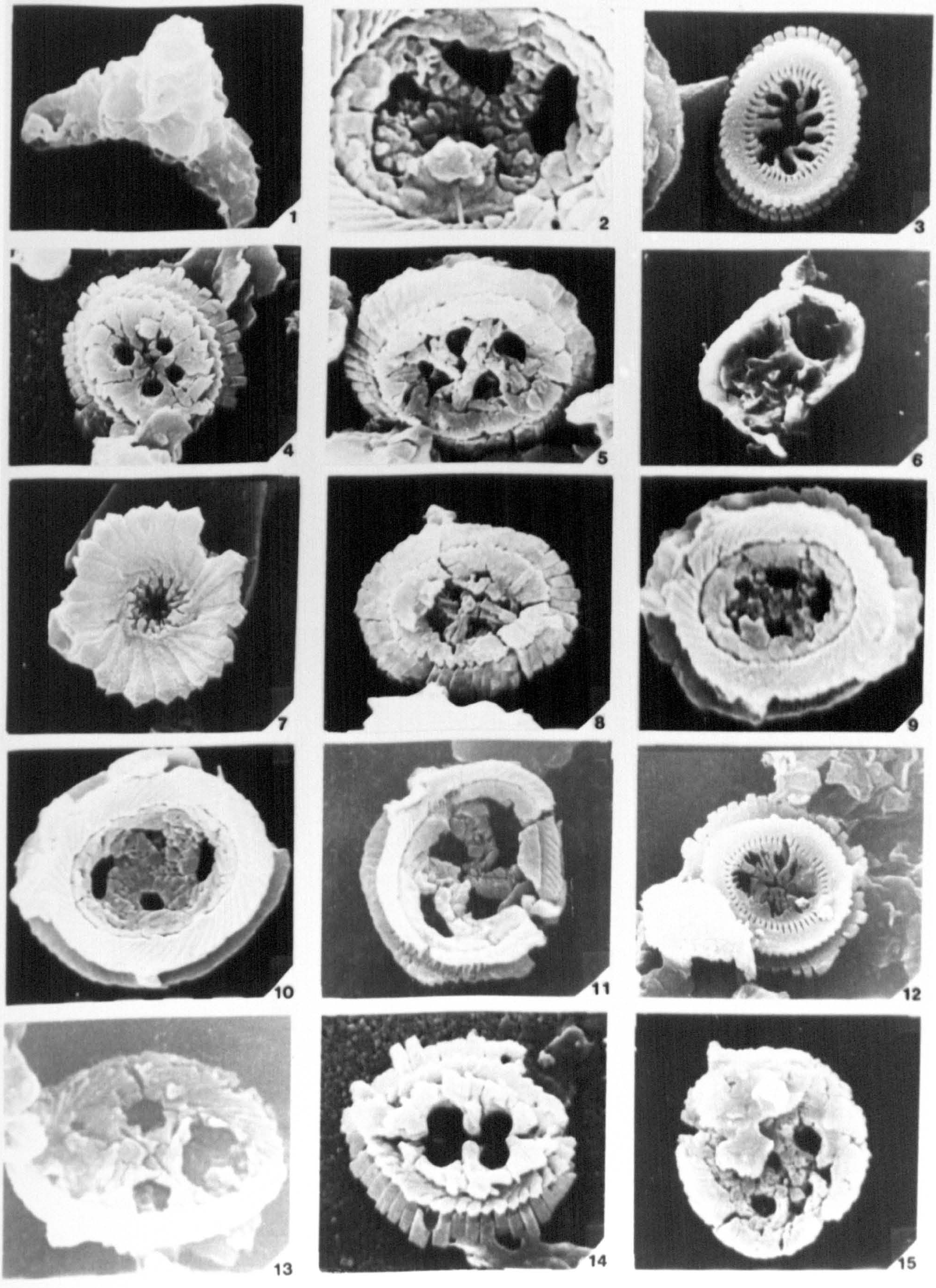
# PLATE 7



## PLATE 8 : SCANNING ELECTRON MICROGRAPHS

1. Tribrachiatus orthostylus Shamrai : UCL-2649-13 poorly preserved specimen. Shell/Esso North Sea well number 49/10-1, depth 2850'. Early Eocene. X5,000.
2,5,10 & 11. Chiasmolithus edentulus Van Heck and Prins : Fig.2 UCL-2309-04 central area detail (X10,000); Fig.5 UCL-2309-14 distal view; Fig.10 UCL-2309-15 proximal view; Fig.11 UCL-2650-11 proximal view. Shell/Esso North Sea well number 21/11-1, depth 5240'. Early Palaeocene. X5,000.
3. Toweius pertusus (Sullivan) Romein : UCL-2433-10 proximal view. AG16. Pegwell Bay, Kent. Late Palaeocene. X7,500.
4. Toweius eminens (Bramlette and Sullivan) Perch-Nielsen : UCL-2583-13 distal view of an overgrown specimen. Ag16. Pegwell Bay, Kent. Late Palaeocene. X5,000.
6. Neochiastozygus perfectus Perch-Nielsen : UCL-2566-04 very poorly preserved. Shell/Esso North Sea well number 21/30-1, depth 6742'. Early Palaeocene. X3,750.
7. Heliolithus riedelii Bramlette and Sullivan : UCL-2433-09 top view. AG16. Pegwell Bay, Kent. Late Palaeocene. X5,000.
8. Chiasmolithus inconspicuus Van Heck and Prins : UCL-2309-12 distal view. Shell/Esso North Sea well number 21/11-1, depth 5240'. Early Palaeocene. X5,000.
9. Chiasmolithus edentulus Van Heck and Prins : UCL-2309-03 proximal view. Shell/Esso North Sea well number 21/11-1, depth 5240'. Early Palaeocene. X7,500.
12. Toweius tovae Perch-Nielsen : UCL-2433-06 proximal view. AG16. Pegwell Bay, Kent. Late Palaeocene. X5,000.
13. Neochiastozygus perfectus Perch-Nielsen : UCL-2337-25 distal view, overgrown specimen. Shell/Esso North Sea well number 21/11-1, depth 5240'. Early Palaeocene. X7,500.
14. Toweius eminens (Bramlette and Sullivan) Perch-Nielsen : UCL-2583-11 distal view. AG16. Pegwell Bay, Kent. Late Palaeocene. X7,500.
15. Thoracosphaera operculata Bramlette and Martini : UCL-2309-13 operculum only. Shell/Esso North Sea well number 21/11-1, depth 5240'. Early Palaeocene. X5,000.

# PLATE 8



## PLATE 9 : SCANNING ELECTRON MICROGRAPHS

1 & 2. Neocrepidolithus neocrassus (Perch-Nielsen) Romein : Fig.1 UCL-2337-32 distal view; Fig.2 UCL-2309-01 distal view. Shell/Esso North Sea well number 21/11-1, depth 5240'. Early Palaeocene. X10,000.

3. Placozygus sigmoides (Bramlette and Sullivan) Romein : UCL-2566-02 oblique distal view. Shell/Esso North Sea well number 21/30-1, depth 6742'. Early Palaeocene. X5,000.

4. Prinsius dimorphosus (Perch-Nielsen) Perch-Nielsen : UCL-2553-12 distal view. Shell/Esso North Sea well number 30/19a-2, depth 9096'. Early Palaeocene. X5,000.

5 & 6. Chiasmolithus inconspicuus Van Heck and Prins : Fig.5 UCL-2553-07 distal view; Fig.6 UCL-2553-09 distal view. Shell/Esso North Sea well number 30/19a-2, depth 9096'. Early Palaeocene. X5,000.

7. Chiasmolithus edentulus Van Heck and Prins : UCL-2337-17 oblique distal view. Shell/Esso North Sea well number 21/11-1, depth 5240'. Early Palaeocene. X5,000.

8 & 10. Toweius tovae Perch-Nielsen : Fig.8 UCL-2433-11 distal view; Fig.10 UCL-2582-03 distal view. AG16. Pegwell Bay, Kent. Late Palaeocene. X7,500.

9. Toweius tovae?Perch-Nielsen : UCL-2583-20 distal view. AG16. Pegwell Bay, Kent. Late Palaeocene. X7,500.

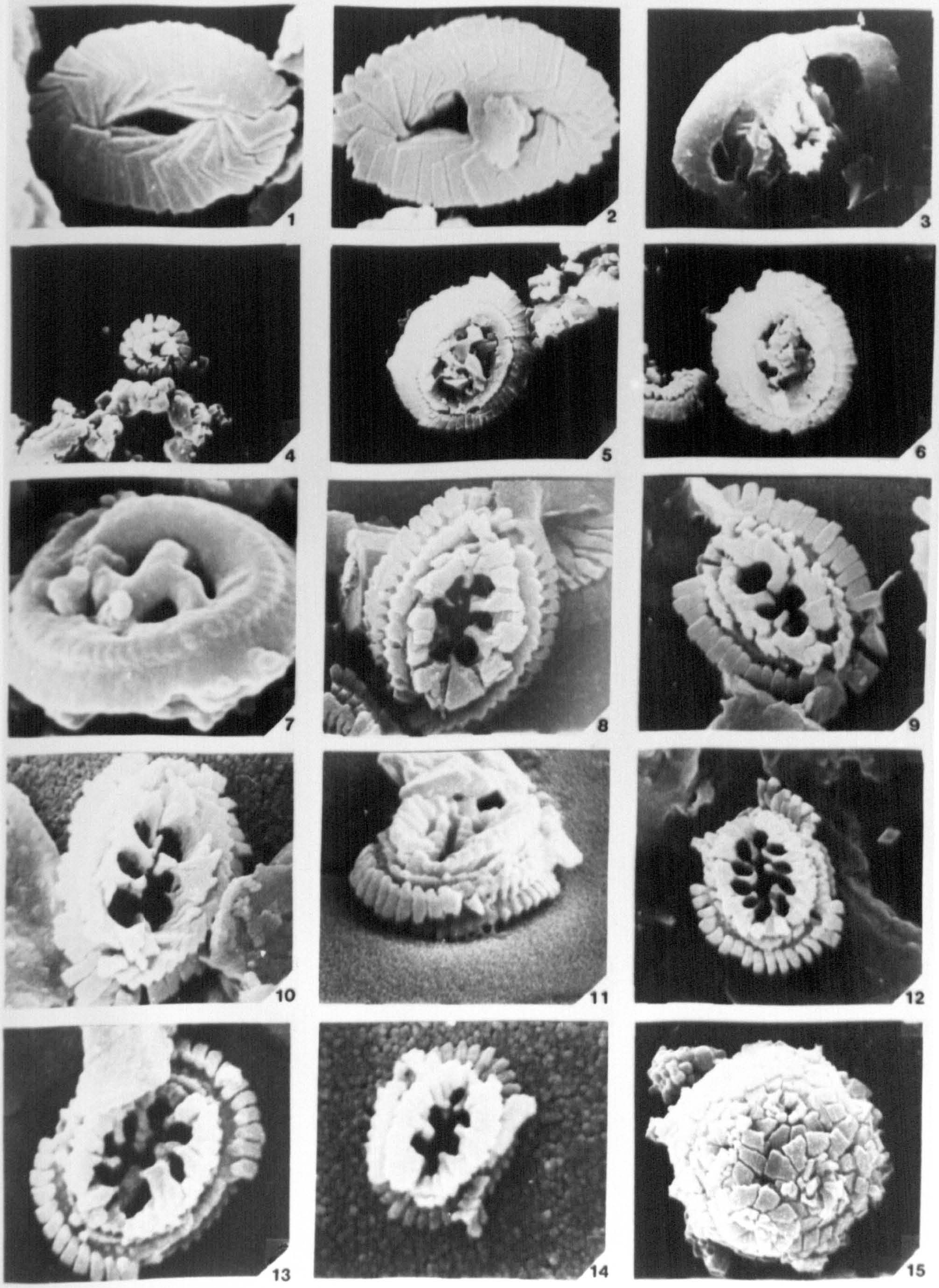
11 & 13. Toweius pertusus (Sullivan) Romein : Fig.11 UCL-2582-21 Side view of an etched specimen; Fig.13 UCL-2582-23. AG16. Pegwell Bay, Kent. Late Palaeocene. X10,000.

12. Toweius pertusus (Sullivan) Romein : UCL-2583-21 distal view of an etched specimen. AG16. Pegwell Bay, Kent. Late Palaeocene. X7,500.

14. Toweius sp. : UCL-2583-02 distal view of a broken specimen. AG16. Pegwell Bay, Kent. Late Palaeocene. X10,000.

15. Prinsius dimorphosus (Perch-Nielsen) Perch-Nielsen : UCL-2462-35 coccosphere. Shell/Esso North Sea well number 30/19a-2, depth 9096'. Early Palaeocene. X7,500.

# PLATE 9



## PLATE 10 : LIGHT MICROGRAPHS

All prints X2000 magnification.

1 & 2. Helicosphaera sellii Bukry and Bramlette : Fig.1 UCL-2226-05 phase contrast; Fig.2 UCL-2226-04 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 4210'. Late Miocene.

3,4,7 & 8. Helicosphaera stalis Theodoridis : Fig.3 UCL-2206-17 phase contrast; Fig.4 UCL-2206-18 crossed-nicols; Fig.7 UCL-2226-09 phase contrast; Fig.8 UCL-2226-08 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 4700'. Middle Miocene.

5. Lithostromation perdurum Deflandre : UCL-2187-07 phase contrast. Shell/Esso North Sea well number 29/10-1, depth 4810'. Middle Miocene.

6. Reticulofenestra pseudoumbilicus (Gartner) Gartner : UCL-2185-08 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 4810'. Middle Miocene.

9 & 10. Calcidiscus leptoporus (Murray and Blackman) Loeblich and Tappan : Fig.9 UCL-2211-03 phase contrast; Fig.10 UCL-2211-04 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 4250'. Late Miocene.

11,12 & 15. Helicosphaera ampliaperta Bramlette and Wilcoxon : Fig.11 UCL-2192-04 phase contrast; Fig.12 UCL-2192-02 crossed-nicols; Fig.15 UCL-2192-07 phase contrast. Shell/Esso North Sea well number 29/10-1, depth 5796'. Early Miocene.

13. Discoaster deflandrei Bramlette and Riedel : UCL-2185-23 phase contrast. Shell/Esso North Sea well number 29/10-1, depth 5100'. Middle Miocene.

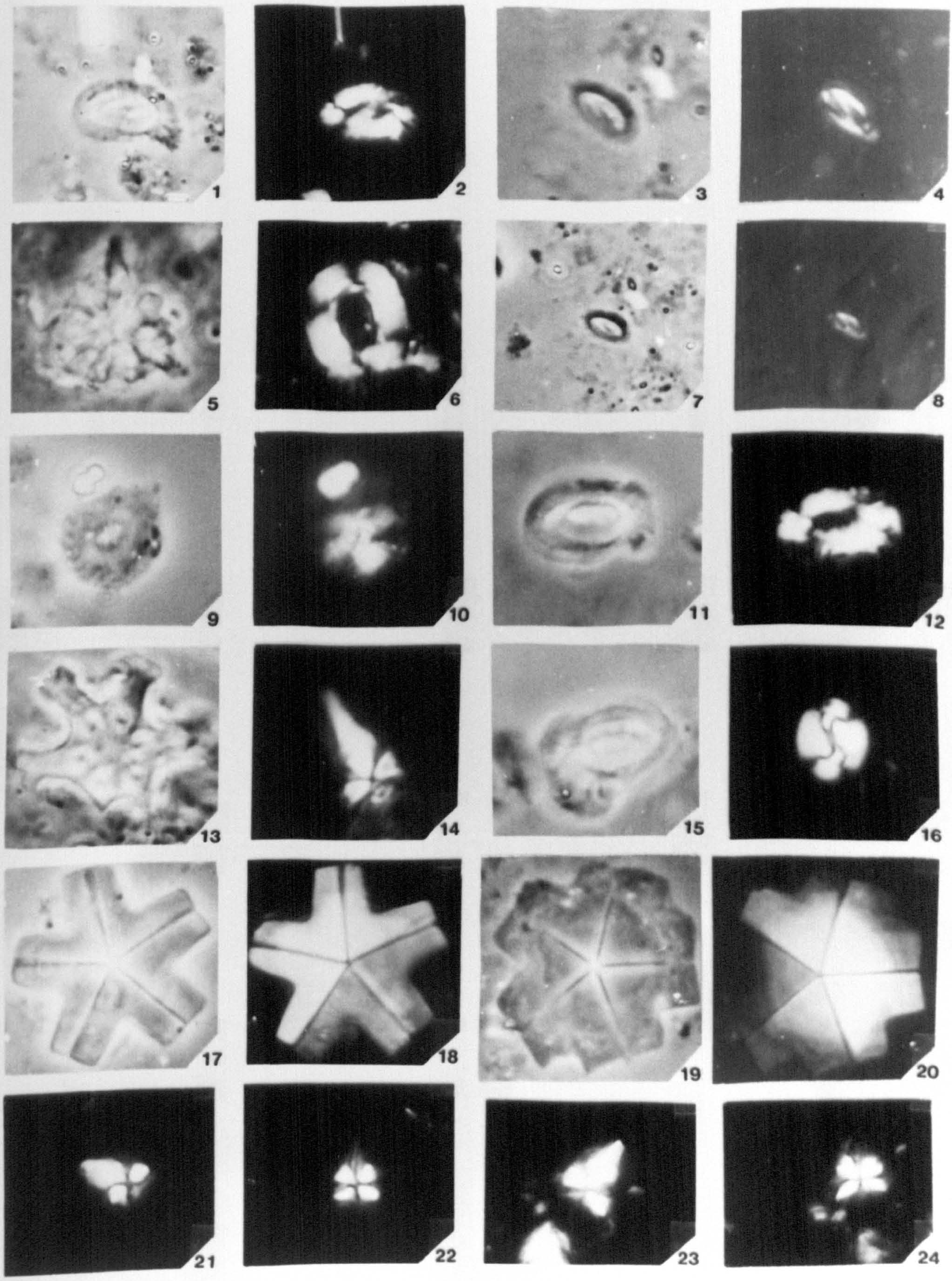
14,21,22,23 & 24. Sphenolithus heteromorphus Deflandre : Fig.14 UCL-2206-12 crossed-nicols, 45°; Fig.21 UCL-2206-01 crossed-nicols, 45°; Fig.22 UCL-2206-02 crossed-nicols, 0°; Fig.23 UCL-2226-19 crossed-nicols, 45°; Fig.24 UCL-2226-18 crossed-nicols, 0°. Shell/Esso North Sea well number 29/10-1, depth 5660'. Middle Miocene.

16. Reticulofenestra productellus (Bukry) n. comb. : UCL-2206-19 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 4700'. Middle Miocene.

17 & 18. Micrantholithus aequalis Sullivan : Fig.17 UCL-2183-25 phase contrast; Fig.18 UCL-2183-24 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 4790'. Middle Miocene.

19 & 20. Micrantholithus truncus Bramlette and Sullivan : Fig.19 UCL-2183-20 phase contrast; Fig.20 UCL-2183-19 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 4790'. Middle Miocene.

# PLATE 10



## PLATE 11 : LIGHT MICROGRAPHS

All micrographs X2000 magnification.

1 - 8. Sphenolithus belemnos Bramlette and Wilcoxon : Fig.1 UCL-2243-14, 45°; Fig.2 UCL-2226-20, 45°; Fig.3 UCL-2243-21, 45°; Fig.4 UCL-2243-26, 45°; Fig.5 UCL-2243-15, 0°; Fig.6 UCL-2226-21, 0°;Fig.7 UCL-2243-22, 0°; Fig.8 UCL-2243-27, 0°. Figs.2,6 Shell/Esso North Sea well number 29/10-1, depth 5790'. Figs.1,3-5,7,8 Shell/Esso North Sea well number 21/11-1, depth 2393'. Early Miocene. All figures crossed-nicols.

9 & 10. Micrantholithus vesper Deflandre : Fig.9 UCL-2211-20 phase contrast; Fig.10 UCL-2211-19 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 6850'. Late Oligocene.

11 & 23. Discoaster deflandrei Bramlette and Riedel : Fig.11 UCL-2192-10 phase contrast; Fig.23 UCL-2192-24 phase contrast. Shell/Esso North Sea well number 29/10-1, depth 5796'. Early Miocene.

12,15 & 16. Helicosphaera mediterranea Muller : Fig.12 UCL-2243-29 crossed-nicols; Fig.15 UCL-2243-28 phase contrast; Fig.16 UCL-2243-03 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 2393'. Early Miocene.

13 & 14. Pontosphaera multipora (Kamptner) Roth : Fig.13 UCL-2185-31 phase contrast; Fig.14 UCL-2185-30 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 5100'. Middle Miocene.

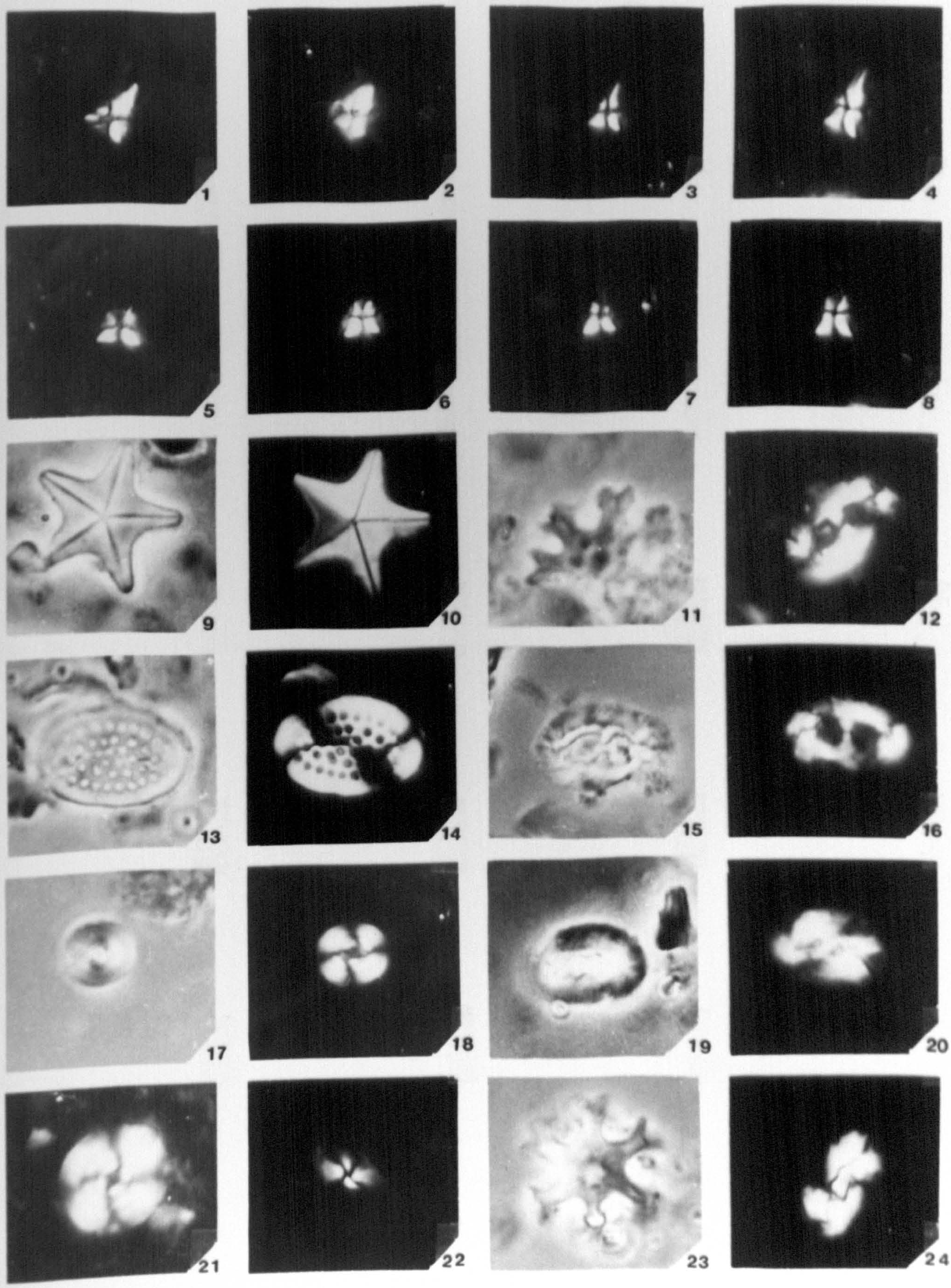
17 & 18. Cyclicargolithus floridanus (Roth and Hay) Bukry : Fig.17 UCL-2243-06 phase contrast; Fig.18 UCL-2243-05 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 2393'. Early Miocene.

19,20 & 24. Helicosphaera euphratis Haq : Fig.19 UCL-2202-08 phase contrast; Fig.20 UCL-2202-07 crossed-nicols; Fig.24 UCL-2202-09 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 6950'. Late Oligocene.

21. Cyclicargolithus abisectus (Muller) Wise : UCL-2192-14 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 5785'. Early Miocene.

22. Syracosphaera histrica Kamptner : UCL-2202-11 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 6950'. Late Oligocene.

# PLATE 11



## PLATE 12 : LIGHT MICROGRAPHS

All micrographs X2000 magnification.

1,2 & 22. Zygrhablithus bijugatus (Deflandre) Deflandre : Fig.1 UCL-2187-20 phase contrast; Fig.2 UCL-2187-21 crossed-nicols; Fig.22 UCL-2187-19 crossed-nicols, top view. Shell/Esso North Sea well number 29/10-1, depth 7122'. Early Oligocene.

3 & 4. Chiasmolithus altus Bukry and Percival : Fig.3 UCL-2187-17 phase contrast; Fig.4 UCL-2187-16 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 7100'. Late Oligocene.

5,6 & 21. Chiasmolithus altus Bukry and Percival : Fig.5 UCL-2351-04 phase contrast; Fig.6 UCL-2351-03 crossed-nicols; Fig.21 UCL-2351-08 phase contrast. DSDP-12-117-2-3 147-148cm. Late Oligocene.

7 & 8. Zygrhablithus bijugatus (Deflandre) Deflandre : Fig.7 UCL-2211-14 phase contrast; Fig.8 UCL-2211-13 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 6850'. Late Oligocene.

9 & 10. Helicosphaera recta Haq : Fig.9 UCL-2202-04 phase contrast; Fig.10 UCL-2202-03 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 7488'. (caved) Early Oligocene.

11 & 12. Lanternithus minutus Stradner : Fig.11 UCL-2526-33 phase contrast; Fig.12 UCL-2526-32 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 1737'. Middle Eocene.

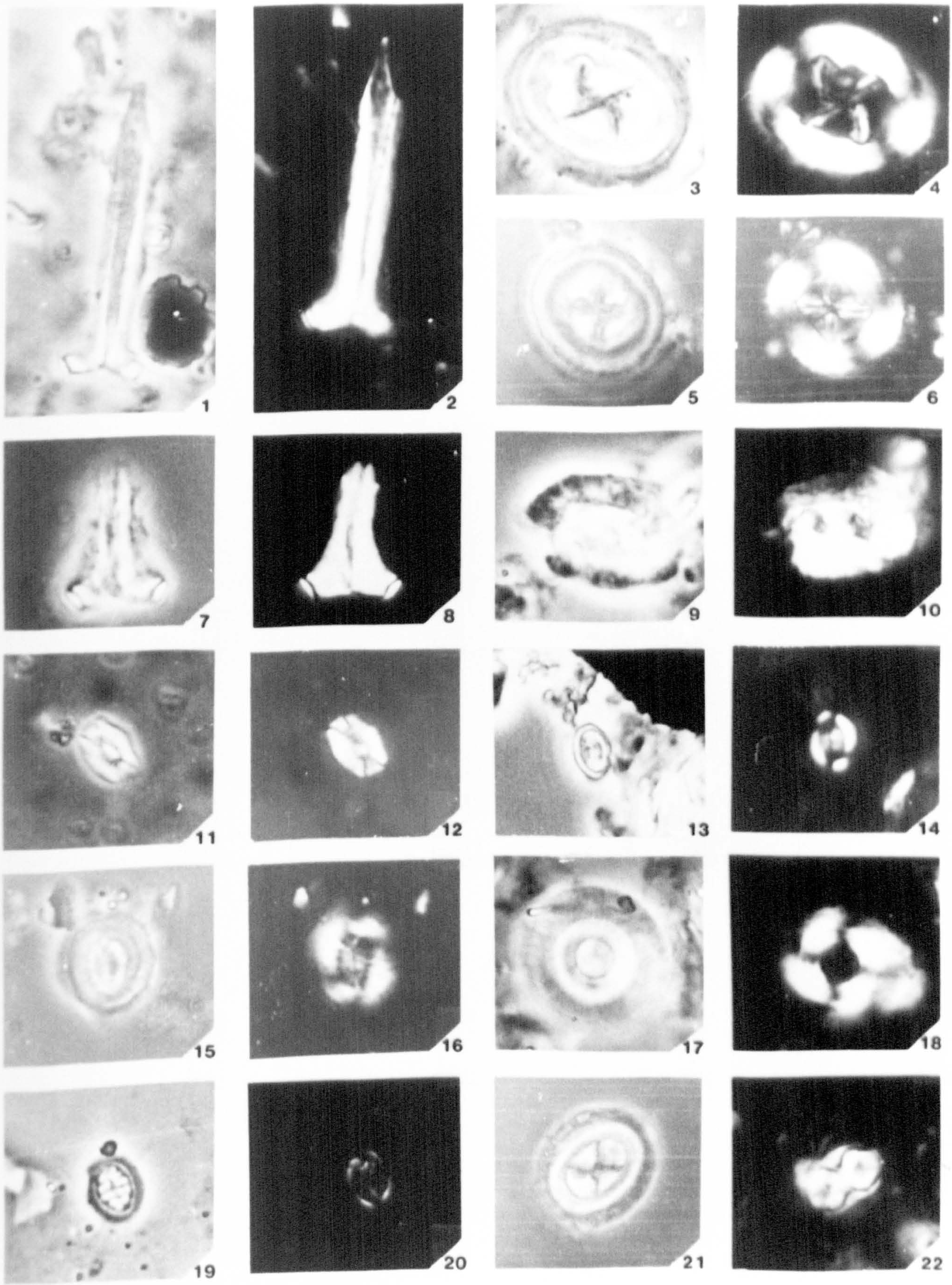
13 & 14. Reticulofenestra foveolata (Reinhardt) Roth : Fig.13 UCL-2385-08 phase contrast; Fig.14 UCL-2385-07 crossed-nicols. S136/898. William's Bluff, Oamaru, New Zealand. Early Oligocene.

15 & 16. Reticulofenestra daviesii (Haq) Haq : Fig.15 UCL-2250-17 phase contrast; Fig.16 2250-16 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 4300'. (caved) Late Eocene.

17 & 18. Ericsonia formosa (Kamptner) Haq : Fig.17 UCL-2187-09 phase contrast; Fig.18 UCL-2187-10 crossed-nicols. Shell/Esso North Sea well number 29/10-1, depth 7122'. Early Oligocene.

19 & 20. Ericsonia obruta Perch-Nielsen : Fig.19 UCL-2295-11 phase contrast; Fig.20 UCL-2295-12 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene.

# PLATE 12



## PLATE 13 : LIGHT MICROGRAPHS

All micrographs X2000

1. Isthmolithus recurvus Deflandre : UCL-2195-13 phase contrast. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene.

2. Sphenolithus predistentus Bramlette and Wilcoxon : UCL-2526-22 crossed-nicols. A57. St. Stephen's Quarry, Alabama, U.S.A. Middle Eocene.

3 & 4. Ericsonia subdisticha (Roth) Roth : Fig.3 UCL-2479-20 phase contrast; Fig.4 UCL-2479-21 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 1697'. Middle Eocene.

5 & 6. Isthmolithus recurvus Deflandre : Fig.5 UCL-2479-06 phase contrast; Fig.6 UCL-2479-05 crossed-nicols. Shell/Esso North Sea well number 49/9-1, 1288'. Late Eocene.

7 & 8. Transversopontis pulchra (Deflandre) Perch-Nielsen : Fig.7 UCL-2250-11 phase contrast; Fig.8 UCL-2250-10 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 4300' (caved). Late Eocene.

9 & 10. Chiasmolithus nitidus Perch-Nielsen : Fig.9 UCL-2526-16 phase contrast; Fig.10 UCL-2526-15 crossed-nicols. A57. Stephen's Quarry, Alabama, U.S.A. Middle Eocene.

11 & 12. Pemma papillatum Martini : Fig.11 UCL-2526-02 phase contrast; Fig.12 UCL-2526-01 crossed-nicols. A57. Stephen's Quarry, Alabama, U.S.A. Middle Eocene.

13 & 14. Corannulus germanicus Stradner : Fig.13 UCL-2250-04 phase contrast; Fig.14 UCL-2250-03 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 4300' (caved). Late Eocene.

15 & 16. Chiasmolithus oamaruensis (Deflandre) Hay, Mohler and Wade : Fig.15 UCL-2250-09 phase contrast; Fig.16. UCL-2250-08 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 4300' (caved). Late Eocene.

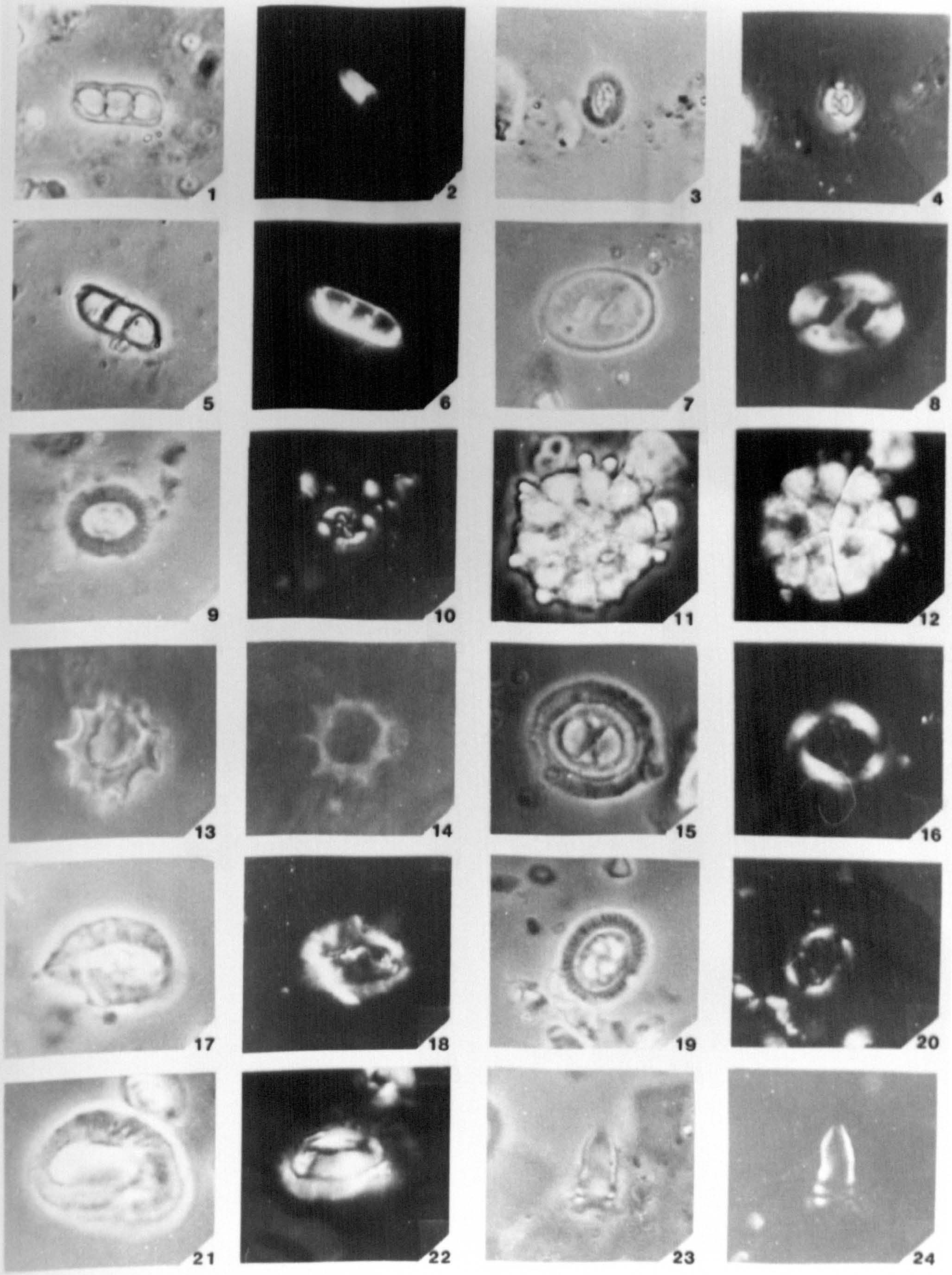
17 & 18. Helicosphaera reticulata Bramlette and Wilcoxon : Fig.17 UCL-2526-25 phase contrast; Fig.18 UCL-2526-24 crossed-nicols. A57. Stephen's Quarry, Alabama, U.S.A. Middle Eocene.

19 & 20. Chiasmolithus titus Gartner : Fig.19 UCL-2526-30 phase contrast; Fig.20 UCL-2526-31 crossed-nicols. A57. Stephen's Quarry, Alabama, U.S.A. Middle Eocene.

21 & 22. Helicosphaera compacta Bramlette and Wilcoxon : Fig.21 UCL-2526-09 phase contrast; Fig.22 UCL-2526-08 crossed-nicols. A57. Stephen's Quarry, Alabama, U.S.A. Middle Eocene.

23 & 24. Rhabdosphaera pseudomorionum Locker : Fig.23 UCL-2526-35 phase contrast; Fig.24 UCL-2526-34. Shell/Esso North Sea well number 49/9-1, depth 1737'. Middle Eocene.

# PLATE 13



## PLATE 14 : LIGHT MICROGRAPHS

All micrographs X2000 magnification

1 & 2. Sphenolithus furcatolithoides Locker : Fig.1 UCL-2499-11 phase contrast; Fig.2 UCL-2499-10 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 1890'. Middle Eocene.

3 & 4. Neococcolithes minutus (Perch-Nielsen) Perch-Nielsen : Fig.3 UCL-2479-23 phase contrast; Fig.4 UCL-2479-24 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 1737'. Middle Eocene.

5. Sphenolithus furcatolithoides Locker : UCL-2479-07 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 1535'. Middle Eocene.

6. Sphenolithus furcatolithoides Locker : UCL-2479-17 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 1637'. Middle Eocene.

7 & 8. Ericsonia formosa (Kamptner) Haq : Fig.7 UCL-2295-09 phase contrast; Fig.8 UCL-2295-10 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene.

9 & 10. Birkelundia staurion (Bramlette and Sullivan) Perch-Nielsen : Fig.9 UCL-2479-34 phase contrast; Fig.10 UCL-2479-33 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 1737'. Middle Eocene.

11. Discoaster barbadiensis : Fig.11 UCL-2446-30 phase contrast. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene.

12 & 20. Helicosphaera compacta Bramlette and Wilcoxon : Fig.12 UCL-2254-01 crossed-nicols; Fig.20 UCL-2254-02 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene.

13 & 14. Rhabdosphaera gladius Locker : Fig.13 UCL-2479-29 phase contrast; Fig.14 UCL-2479-28 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 1737'. Middle Eocene.

15 & 16. Ericsonia formosa (Kamptner) Haq : Fig.15 UCL-244631 phase contrast; Fig.16 UCL-2446-32 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 3050'. Late Eocene.

17. Clathrolithus spinosus Martini : UCL-2479-30 phase contrast. Shell/Esso North Sea well number 49/9-1, depth 1737'. Middle Eocene.

18. Discoaster saipanensis Bramlette and Riedel : UCL-2392-30 phase contrast. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher bed XVII, 0.5m above base. Middle Eocene.

19. Discoaster binodosus Martini : UCL-2346a-31 phase contrast. HB768. Hampden Beach, New Zealand. Late Eocene.

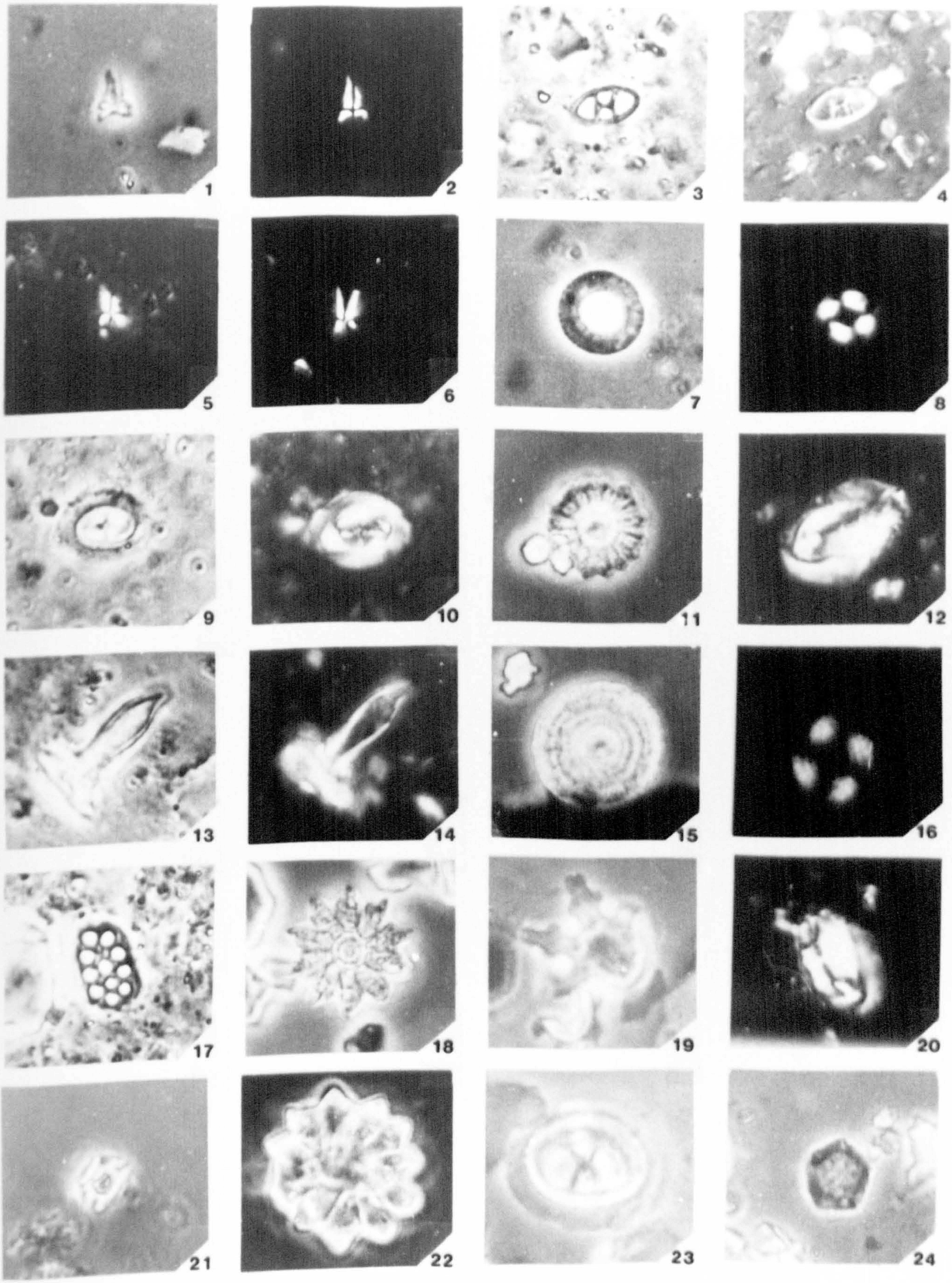
21. Lanternithus minutus Stradner : UCL-2250-13 phase contrast. Shell/Esso North Sea well number 21/11-1, depth 4300' (caved). Late Eocene.

22. Discoaster barbadiensis Tan : UCL-2526-19 phase contrast. A57. Stephen's Quarry, Alabama, U.S.A. Middle Eocene.

23. Chiasmolithus oamaruensis (Deflandre) Hay, Mohler and Wade : UCL-2346a-32 phase contrast. HB768. Hampden Beach, New Zealand. Late Eocene.

24. Goniolithus fluckigeri Deflandre : UCL-2526-10 phase contrast. A57. Stephen's Quarry, Alabama, U.S.A. Middle Eocene.

# PLATE 14



## PLATE 15 : LIGHT MICROGRAPHS

All micrographs X2000, except figs.17 & 18 which are X3200

1,2 & 24. Naninfula deflandrei Perch-Nielsen : Fig.1 UCL-2628-11 phase contrast; Fig.2 UCL-2628-10 crossed-nicols; Fig.24 UCL-2540-34 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene.

3 & 4. Helicosphaera reticulata Bramlette and Wilcoxon : Fig.3 UCL-2628-14 phase contrast; Fig.4 UCL-2628-15 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene.

5 & 6. Helicosphaera compacta Bramlette and Wilcoxon : Fig.5 UCL-2479-16 phase contrast; Fig.6 UCL-2479-15 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 1697'. Middle Eocene.

7 & 8. Rhabdosphaera pseudomorionum Locker : Fig.7 UCL-2628-16 phase contrast; Fig.8 UCL-2628-18 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene.

9 & 10. Chiasmolithus expansus (Bramlette and Sullivan) Gartner : Fig.9 UCL-2497-30 phase contrast; Fig.10 UCL-2497-29 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2167'. Middle Eocene.

11 & 12. Pontosphaera plana (Bramlette and Sullivan) Haq : Fig.11 UCL-2545-06 phase contrast; Fig.12 UCL-2545-05 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene.

13 & 14. Chiasmolithus solitus (Bramlette and Sullivan) Locker : Fig.13 UCL-2540-09 phase contrast; Fig.14 UCL-2540-10 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene.

15 & 16. Pemma basquensis (Martini) Baldi-Beke : Fig.15 UCL-2545-04 phase contrast; Fig.16 2545-03 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene.

17 & 18. Reticulofenestra callida (Perch-Nielsen) Bybell : Fig.17 UCL-2638-06 phase contrast; Fig.18 UCL-2638-07 crossed-nicols. Shell/Esso North Sea well number 49/10-1, depth 2600'. Middle Eocene.

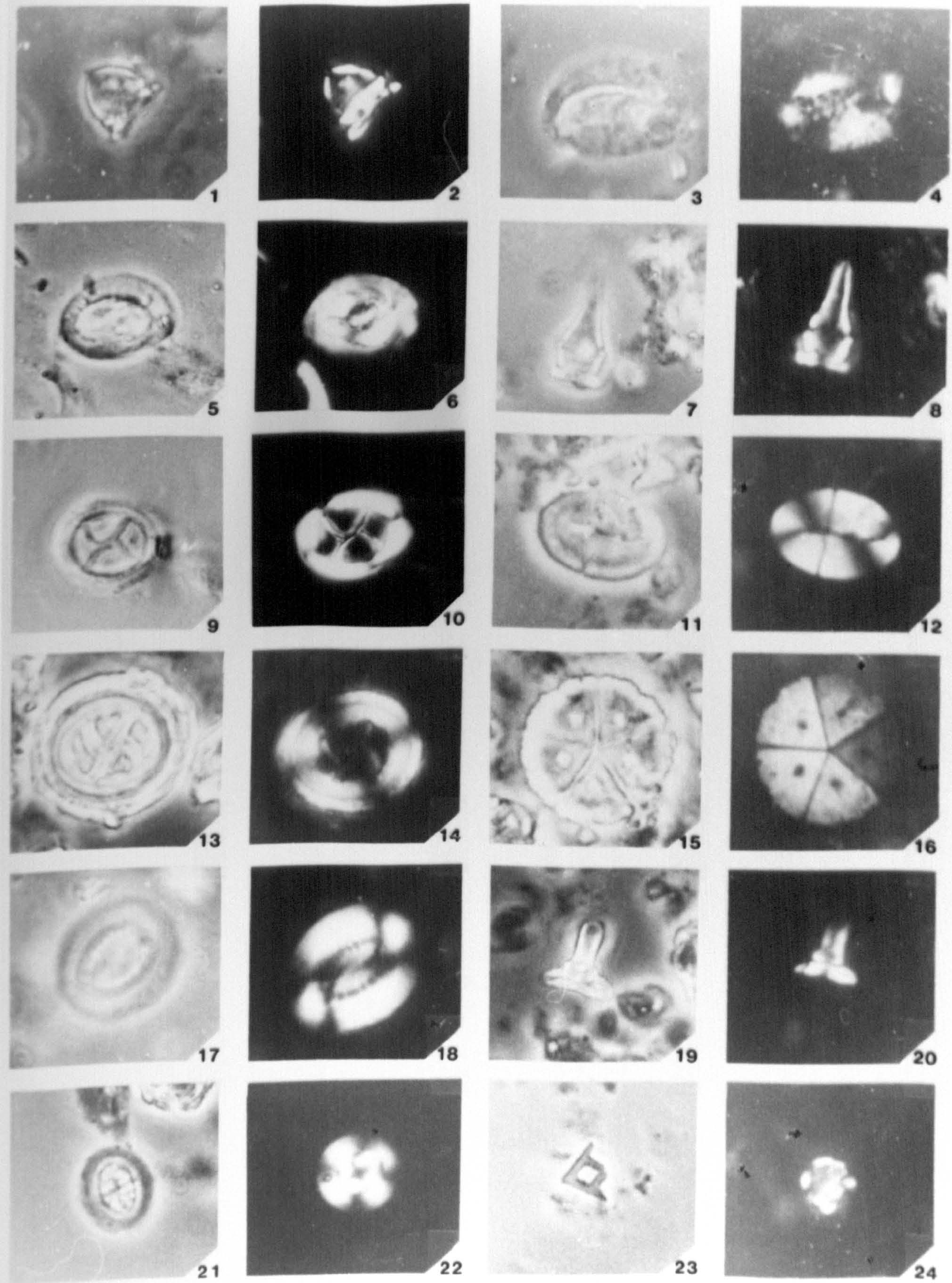
19 & 20. Rhabdosphaera gladius Locker : Fig.19 UCL-2540-17 phase contrast; Fig.20 UCL-2540-18 crossed-nicols. Small specimen. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene.

21. Ericsonia fenestrata (Deflandre and Fert) Stradner : UCL-2638-26 phase contrast. Shell/Esso North Sea well number 49/9-1, depth 2600'. Middle Eocene.

22. Cyclicargolithus floridanus (Roth and Hay) Bukry : UCL-2545-27 crossed-nicols. A61. St. Stephen's Quarry, Alabama, U.S.A.

23. Pemma stradneri (Chang) Bybell and Gartner : UCL-2479-10 phase contrast. Shell/Esso North Sea well number 49/9-1, depth 1535'. Middle Eocene.

# PLATE 15



## PLATE 16 : LIGHT MICROGRAPHS

All micrographs X2000 magnification, except figs.5,6,7 & 8 which are X3200

1 & 2. Helicosphaera lophota Bramlette and Sullivan : Fig.1 UCL-2540-22 phase contrast; Fig.2 UCL-2540-21 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene.

3,4 & 16. Naninfula deflandrei Perch-Nielsen : Fig.3 UCL-2499-16 crossed-nicols; Fig.4 2499-02 phase contrast; Fig.16 UCL-2499-17 phase contrast. Shell/Esso North Sea well number 49/9-1, depth 1890'. Middle Eocene.

5 & 6. Helicosphaera seminulum Bramlette and Sullivan : Fig.5 UCL-2638-09 phase contrast; Fig.6 UCL-2638-08 crossed-nicols. Shell/Esso North Sea well number 49/10-1, depth 2600'. Middle Eocene.

7 & 8. Naninfula deflandrei Perch-Nielsen : Fig.7 UCL-2638-10 crossed-nicols; Fig.8 UCL-2638-11 phase contrast. Shell/Esso North Sea well number 49/10-1, depth 2600'. Middle Eocene.

9,10 & 24. Discoaster kuepperi Stradner : Fig.9 UCL-2499-25 phase contrast; Fig.10 UCL-2499-26 crossed-nicols; Fig.24 UCL-2628-12 phase contrast. Shell/Esso North Sea well number 49/9-1, depth 2490'. Middle Eocene.

11,12,15 & 20. Naninfula deflandrei Perch-Nielsen : Fig.11 UCL-2540-13 crossed-nicols; Fig.12 UCL-2540-14 phase contrast; Fig.15 UCL-2540-11 crossed-nicols; Fig.20 UCL-2540-27 phase contrast. Shell/Esso North Sea well number 49/9-1, depth 2026'. Middle Eocene.

13 & 14. Pontosphaera exilis (Bramlette and Sullivan) Romein : Fig.13 UCL-2499-20 phase contrast; Fig.14 UCL-2499-19 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2490'. Early Eocene.

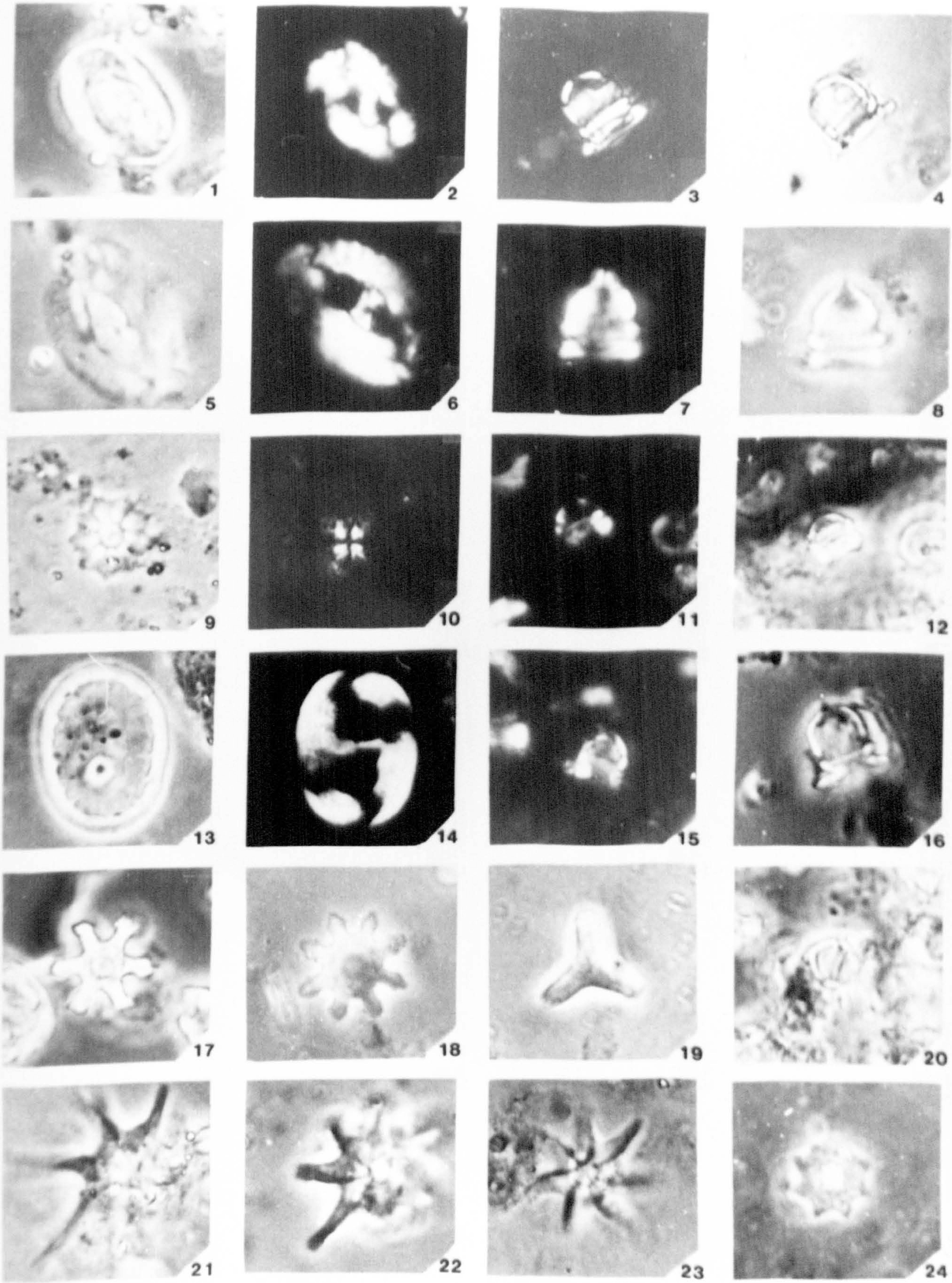
17. Discoaster distinctus Martini : UCL-2392-33 phase contrast. Whitecliff Bay, Bracklesham Group, Selsey Sand Formation, Fisher Bed XVII, 0.5m above base. Middle Eocene.

18. Discoaster binodosus Martini : UCL-2351-34 phase contrast. Parliament Hill sample number 3, North London. Early Eocene.

19. Tribrachiatus orthostylus Shamrai : UCL-2339-14 phase contrast. Parliament Hill sample number 3, North London. Early Eocene.

21,22 & 23. Discoaster lodoensis Bramlette and Riedel : Fig.21 UCL-2499-22 phase contrast; Fig.22 UCL-2499-21 phase contrast; Fig.23 UCl-2499-29 phase contrast. Shell/Esso North Sea well number 49/9-1, depth 2490'. Middle Eocene.

# PLATE 16



## PLATE 17 : LIGHT MICROGRAPHS

All micrographs X2000

1 & 2. Transversopontis rectipons (Haq) Roth : Fig.1 UCL-2339-04 phase contrast; Fig.2 UCL-2339-03 crossed-nicols. Parliament Hill sample number 3, North London. Early Eocene.

3 & 7. Toweius occultatus (Locker) Perch-Nielsen : Fig.3 UCL-2339-01 phase contrast; Fig.7 UCL-2499-23 phase contrast. Parliament Hill sample number 3, North London. Early Eocene.

4. Pontosphaera exilis (Bramlette and Sullivan) Romein : UCL-2497-19 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2167'. Early Eocene.

5. Sphenolithus anarrhopus Bukry and Bramlette : UCL-2339-07 crossed-nicols. Parliament Hill sample number 3, North London. Early Eocene.

6. Sphenolithus radians Deflandre : UCL-2351-27 crossed-nicols. Parliament Hill sample number 7, North London. Early Eocene.

8. Fasciculithus tympaniformis Hay and Mohler : UCL-2426-28 crossed-nicols. AG16. Pegwell bay, Kent. Late Palaeocene.

9,10,11 & 12. Neochiastozygus perfectus Perch-Nielsen : Fig.9 UCL-2254-19 phase contrast; Fig.10 UCL-2254-18 crossed-nicols; Fig.11 UCL-2295-19 phase contrast; Fig.12 UCl-2295-20 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 5225'. Early Palaeocene.

13 & 14. Toweius tovae Perch-Nielsen : Fig.13 UCL-2426-31 phase contrast; Fig.14 UCL-2426-32 crossed-nicols. AG16. Pegwell Bay, Kent. Late Palaeocene.

15. Chiasmolithus edentulus Van Heck and Prins : UCL-2480-02 phase contrast. Shell/Esso North Sea well number 49/9-1, depth 2698'. Early Palaeocene.

16. Prinsius bisulcus (Stradner) Hay and Mohler : UCL-2480-12 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2698'. Early Palaeocene.

17 & 18. Cruciplacolithus tenuis (Stradner) Hay and Mohler : Fig.17 UCL-2254-23 phase contrast; Fig.18 UCL-2254-22 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 5234'. Early Palaeocene.

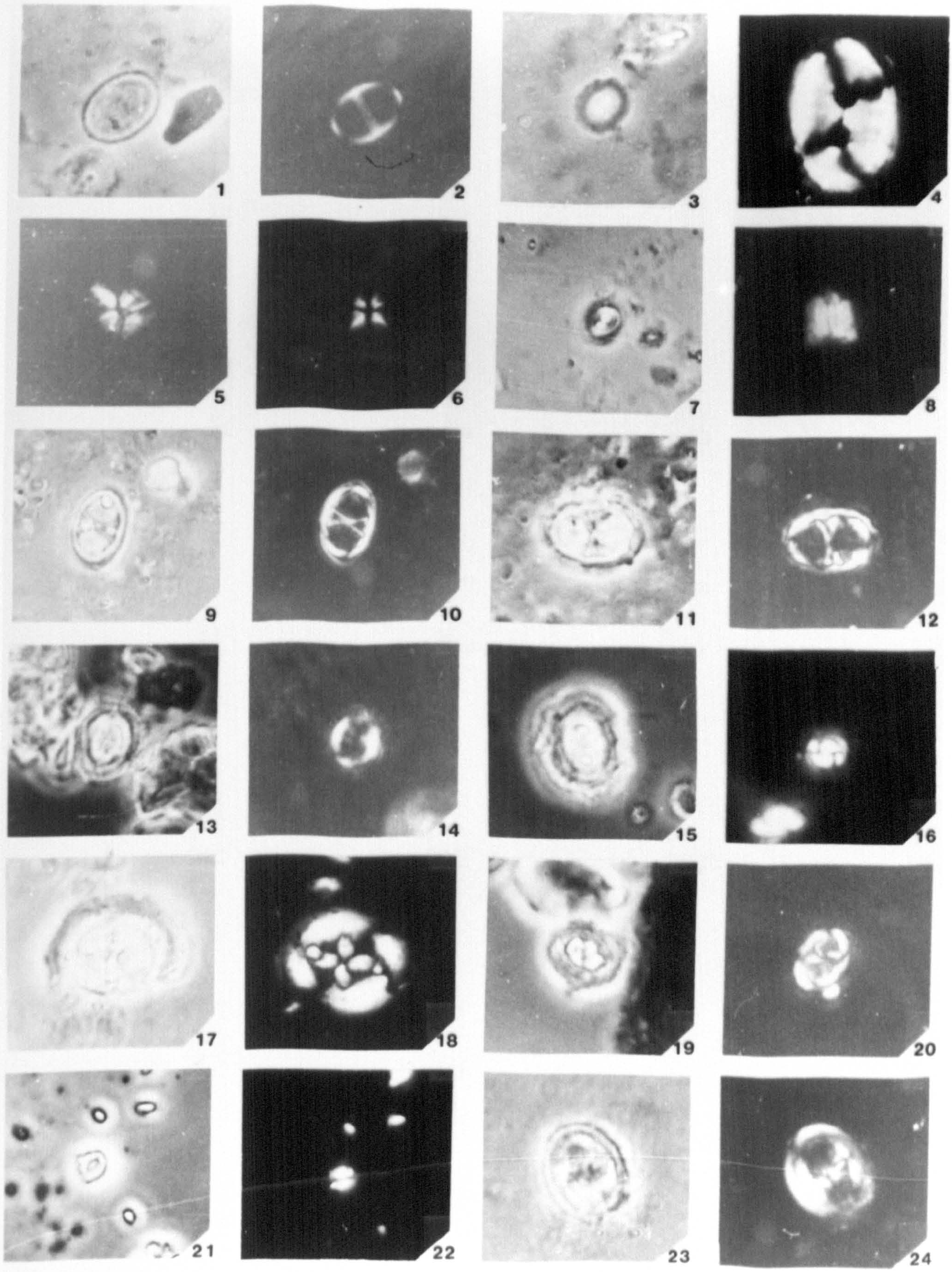
19. Chiasmolithus inconspicuus Van Heck and Prins : UCL-2426-09 phase contrast. AG14. Pegwell Bay, Kent. Late Palaeocene.

20. Neochiastozygus modestus Perch-Nielsen : UCL-2648-17 crossed-nicols. Shell/Esso North Sea well number 30/6-2, depth 9700'. Early Palaeocene.

21 & 22. Prinsius dimorphosus (Perch-Nielsen) Perch-Nielsen : Fig.21 UCL-2480-06 phase contrast; Fig.22 UCL-2480-05 crossed-nicols. Shell/Esso North Sea well number 49/9-1, depth 2698'. Early Palaeocene.

23 & 24. Placozygus sigmoides (Bramlette and Sullivan) Romein : Fig.23 UCL-2254-10 phase contrast; Fig.24 UCL-2254-09 crossed-nicols. Shell/Esso North Sea well number 21/11-1, depth 5234'. Early Palaeocene.

# PLATE 17

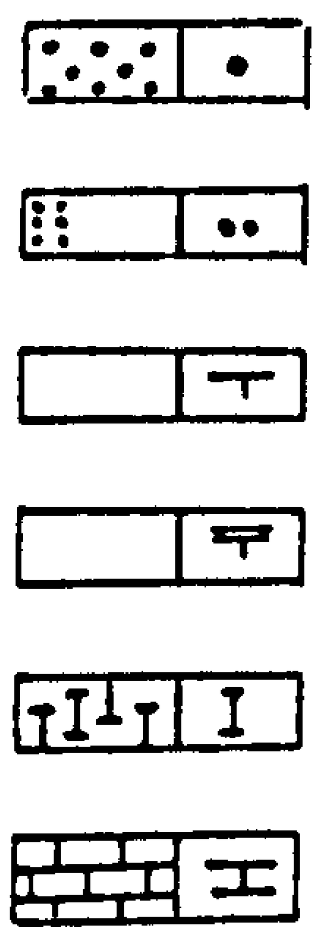


# APPENDICES

APPENDIX 1 : Distribution charts for the following wells -

| | | |
|---|---|---|
| 29/10-1 | 21/11-1 | 21/30-1 |
| 49/9-1 | 16/8-1 | 14/29-1 |
| 29/7-1 | 30/19a-2 | 30/6-2 |
| 49/10-1 | | |

KEY :



Sandstone / Sand

Siltstone / Silt

Claystone / Clay

Shale

Chalk

Limestone

APPENDIX 2 : Range Chart of key species in the North Sea Basin -

Length of line within a zone represents the percentage of samples in that zone in which a particular species occurred. (0.5mm = 1%).

Width of line within a zone represents the percentage of that zone accounted for by a particular species. (See key on Range chart for calibrations).

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